VOL. 65 NO. 3

JOURNAL

of the

AMERICAN SOCIETY

of

NAVAL ENGINEERS, Inc.

AUGUST 1953

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Vol. 65 August, 1953 No. 3

Published Quarterly at Washington, D. C., by The American Society of Naval Engineers, Inc.

Entered as Second Class Matter at the Post Office at Washington, D. C. Acceptance for mailing at special rate of postage provided for in Section 1103. Act of October 3, 1917, authorized on July 3, 1918.

Subscription Rates for Non-Members

The subscription price of the JOURNAL, postpaid to points in the United States and possessions is $9.00. Single copies, $2.25. To other countries, $10.00. Single copies, $2.50. All subscriptions payable in advance.

Make checks, drafts and postal money orders payable to THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

Advertising rates will be furnished on application.

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THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.
605 F Street, N. W.
Washington 4, D. C.

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TABLE OF CONTENTS

PAGE

SECRETARY'S NOTES 505

THE DEVELOPMENT OF ATTACK AIRCRAFT CARRIERS
LT. COMMANDER S. R. HELLER, JR., USN 515

SO, YOU WANT TO BE AN INVENTOR
Journal Franklin Institute, March, 1953 531

THE G-2 TYPE NAVAL GAS TURBINE
The Shipbuilder and Marine Engine-Builder,
February, 1953 538

A RELATIONSHIP FOR PRELIMINARY PROPELLER DIAMETER
EVERS BURTNER 545

TITANIUM — A SURVEY
Engineering, 20 February, 13 March, 27 March, 1953 549

THE PRINCIPLES OF TECHNICAL CONTROL IN
METALLURGICAL MANUFACTURE
Journal of the Institute of Metals, March, 1953 563

SOME USES OF INTERINDUSTRY STATISTICAL TECHNIQUES
H. BURKE HORTON 581

APPARATUS AND PROCEDURES FOR PREDICTING VENTILATION
SYSTEM NOISE
Journal of the Acoustical Society of America,
March, 1953 591

NOISE OF VENTILATING FANS
Journal of the Acoustical Society of America,
March, 1953 605

TRAINING SHOP SUPERVISORS IN PRODUCTION CONTROL
DR. GERALD PAUL STONE 613

WORSHIP OF THE BMEP AND THE NEW MAN ENGINE
P. H. SCHWEITZER 620

PAGE

NEW IDEAS ON LUBRICATION
The British Motor Ship, April, 1953 625

ON THE FUNDAMENTALS OF THE BOUNDARY LAYER THEORY
Journal of the Franklin Institute, April, 1953 629

A RADICAL DEPARTURE IN THE CONVENTIONAL TUGBOAT DESIGN, AND A NEW USE FOR CYCLOIDAL PROPULSION
LT. COMMANDER W. E. FULLER, USN 639

BOOK REVIEWS 646

DEPARTMENTS

DEATHS 649

NEW MEMBERS 650

ASSOCIATION NOTES 653

Editor: Captain J. E. HAMILTON, U.S.N., Ret.

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INDEX TO ADVERTISERS

Name.	Manufacturers of or dealers in	Post office address.	Page
A			
Allis-Chalmers Mfg. Co.	Ship Propulsion and other Equipment for Marine Use	Milwaukee, Wis.	xx
American Brass Co.	Engineering Service on Anaconda Metals	Waterbury, Conn.	xviii
American Chemical Paint Co.	Rust Proofing Chemicals	Ambler, Pa.	xiii
B			
Babcock & Wilcox Co.	Marine Water-Tube Boilers, Superheaters, Airheaters, Economizers, Oil Burners, Refractories, Seamless and Welded Tubing	Room 665, 161 East 42nd St., New York 17, N. Y.	xiv
Bath Iron Works	Shipbuilders and Engineers	Bath, Me.	viii
Bethlehem Steel Co.: Shipbuilding Division	Steam Turbines, Marine Boilers, Oil Burning Equipment, Shipbuilders and Repairers	25 Broadway, New York, N. Y.	xxvi
C			
Cleveland Diesel Engine Division, General Motors Corp.	Diesel Engines	Cleveland, Ohio	xvii
Collins Radio Company	Designers and manufacturers of radio communication and navigation equipment for the Armed Services	Cedar Rapids, Iowa	viii
Cooper-Bessemer Corp., The	Marine Diesel Engines	25 West 43rd St., New York City	iii
Combustion Engineering Co.	Marine Steam Generators, Bent Tube and Straight Tube Boilers, Forced-Circulation Boilers, Superheaters, Economizers and Air Heaters	200 Madison, Ave., New York, N. Y.	I
Crane Co.	Crane Valves	836 S. Michigan Ave., Chicago, Ill.	ii
Cutler-Hammer, Inc.	Electric Control Apparatus	1354 St. Paul Ave., Milwaukee, Wis.	xxi
D			
De Laval Steam Turbine Co.	Steam Turbines	485 Nottingham Way, Trenton, N. J.	x
E			
Electric Boat Co.	Better Submarines for Greater Security	445 Park Avenue, New York 22, N. Y.	xxix
Electric Storage Battery Co.	Exide Batteries	Allegheny Ave. and 19th St., Philadelphia, Pa.	viii
Elliott Co.	Elliott Motors, Generators, Steam and Gas Turbines, Condensers, Deaerating Feedwater Heaters, Turbo Chargers, Strainers, Tube Cleaners, etc.	Jeanette, Pa.	iv

Name.	Manufacturers of or dealers in	Post office address.	Page
F			
Fairchild Engine & Airplane Corporation (Aircraft Division)	Flying Box Cars	Hagerstown, Md.	xxiv
Farrel-Birmingham Co., Inc.	Precision Gears	Ansonia, Connecticut	xii
G			
General Electric	Electric Machinery of All Classes	Schenectady, N. Y.	xxiii
Gibbs & Cox, Inc.	Naval Architects and Engineers	New York, N. Y.	vi
Griscom-Russell Co.	Distilling Plants, Feed Water Heaters	285 Madison Ave., New York	vi
I			
International Nickel Co.	Producers of Nickel	67 Wall St., New York, N. Y.	v
International Telephone and Telegraph Corp.	Communications — Research — Manufacturing	67 Broad St., New York, N. Y.	xxvii
J			
Johns-Manville	Insulation, Refractory Cements, Packings, Brake Linings, Asbestos Ebony for Switch and Panel Boards, Waterproofing Transite Asbestos Sheets, Transite Pipe, Roofing and Shingles, Flooring, Insulating Board Products	22 East 40th St., New York City	viii
K			
Kingsbury Machine Works, Inc.	Thrust Bearings, Journal Bearings, Thrust Meters	Frankford, Philadelphia, Pa.	xv
L			
Lanman Engraving Co.	Photo Engravers	612 L St., N. W., Washington, D. C.	iv
Lidgerwood Industries, Inc.	Steering and Deck Machinery	7 Dey Street, N. Y. 7, N. Y.	xix
M			
Moffitt, Lucian Q., Inc.	Cutless Bearings for Stern Tubes and Struts	Akron, Ohio	iii
N			
Newport News Shipbuilding & Drydock Co.	Naval and Merchant Vessels	Newport News, Va.	ix
New York Shipbuilding Corporation	Shipbuilders	Camden, N. J.	xi
R			
Radio Corporation of America: Govt. Equip. Section	Radio Equipment	Camden, N. J.	xviii
Raytheon Mfg. Co.	Contractors to the Armed Services	Waltham 54, Mass.	xv

Name.	Manufacturers of or dealers in	Post office address.	Page
S			
Selby, Battersby & Co.	Deck Covering for Ships	5220 Whitby Avenue, Philadelphia 43, Pa.	xxi
Sperry Gyroscope Co., Inc.	Radar, Loran, Gyro-Pilots, Gyro-Compasses, Electric and Hydraulic Steering Equipments, Magnetic Compass Pilot, Rudder Angle Indicator, Naval Fire Control Instruments, Aircraft Gyropilots, Flight Instruments	Great Neck, N. Y.	vii
T			
Terry Steam Turbine Co.	Steam Turbines	Hartford, Conn.	xxviii
U			
U. S. Naval Institute	U. S. Naval Institute Proceedings	Annapolis, Md.	xxv
W			
Ward Leonard Electric Co.	Electric Control Devices	Mount Vernon, New York	xxviii
Westinghouse Electric & Mfg. Co.	Marine Steam and Electrical Equipment	East Pittsburgh, Pa.	xvi
Worthington Pump & Machinery Corp.	Pumps, Condensing Apparatus, Diesel Oil Engines, Gas Engines, Fluid Meters, Compressors, Feed Water Heaters	Harrison, N. J.	xxii

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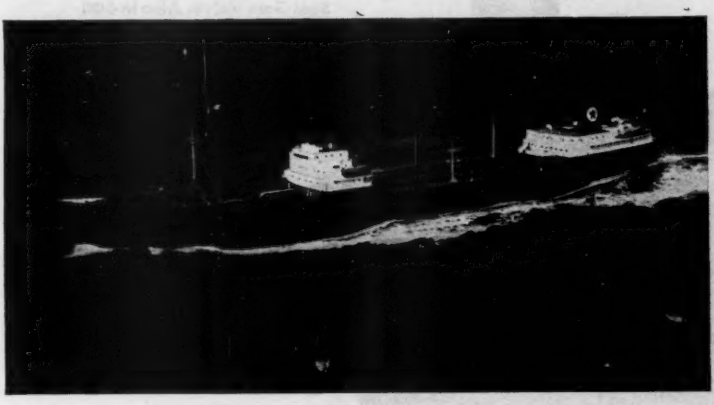

First of four fast new tankers, the S. S. North Dakota has been placed in coastal service by The Texas Company. These ships, designed and built by Newport News Shipbuilding and Drydock Company, have a service speed of 18 knots.

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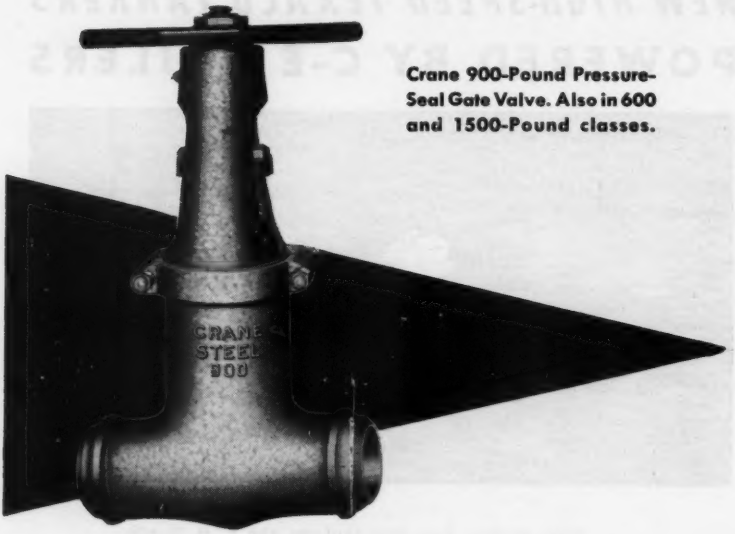

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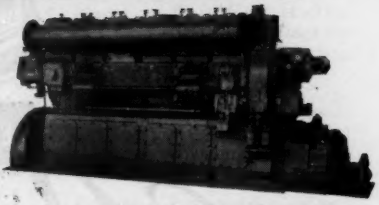

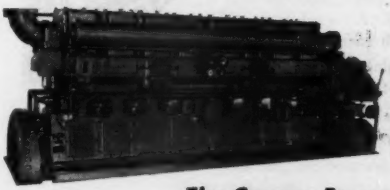

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How Monel shafts helped make LST's good merchantmen

This converted LST, "Dolores," and seven others, out of eleven operated by the SUWANEE S.S. CO., agents, Jacksonville, Fla., now operate on twin screws with high-tensile forged Monel shafts, 6⅛" dia. by 21'. The shafts were machined by the MERRILL-STEVENS DRY DOCK & REPAIR CO., INC., Jacksonville, Fla., and CHARLESTON SHIPYARDS, INC., Charleston, S. C. When the metal situation permits further installation in LST conversions, Monel shafting will be installed throughout the balance of this Suwanee fleet.

Transforming a fleet of LST's into coastal cargo ships had seemed a good idea. But after a few months operation, the SUWANEE S.S. COMPANY, agents, could chart trouble ahead.

For one thing, the 6⅛ in. diameter steel shafts in their new merchantmen had babbitted tail-shaft bearings. They needed lubrication with a grease gun once every watch to try to forstall rusting.

And the steel shafts did not stand up to the constant sand scouring of shallow water operation—plus rust, fatigue, and the blows of floating debris.

Suwanee discussed the problem with a bearing maker and a representative of Inco. And they agreed on an installation of Monel® shafting in B. F. GOODRICH "Cutless" rubber bearings. This would save reboring the stern tube to take a set of Monel sleeves on the steel shafts, as well as eliminating the bearing lubrication problem.

That's exactly what they did — and eight months later when the installation was inspected, Monel shafts and rubber bearings showed no signs of wear or corrosion!

Said Mr. L. Louis Green, Jr., of Suwanee, "The shafts looked as good as new when we hauled the 'Dolores' out in drydock. Eight months of rugged duty between Trinidad and Dutch Guiana convinced us that Monel shafting and 'Cutless' rubber bearings are the best materials for installation on vessels of this type.

"In fact, we were so convinced that we have installed Monel shafts on seven other converted LST ships."

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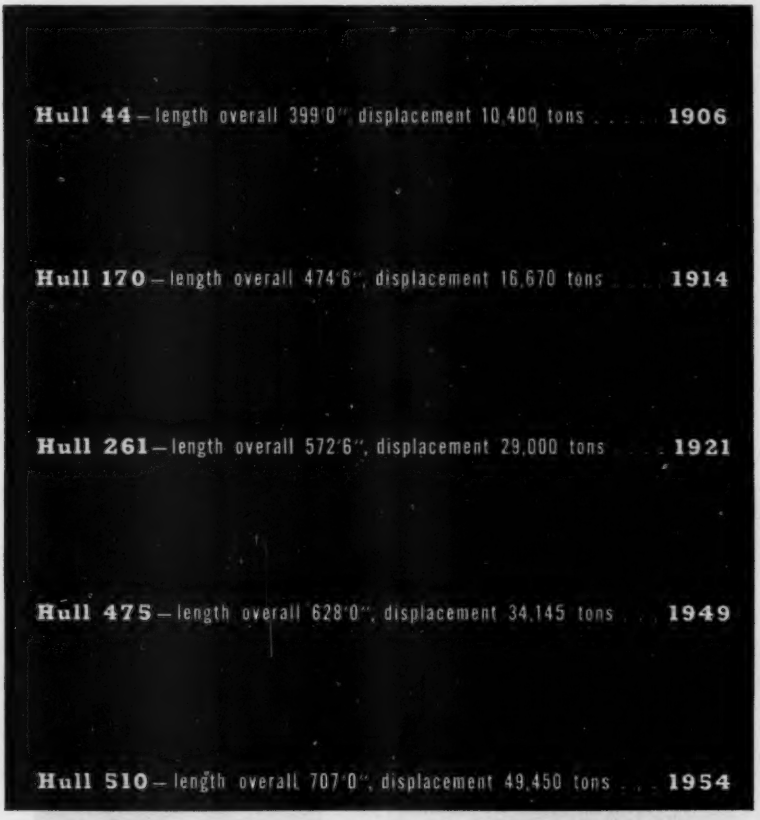
Hull 44 – length overall 399'0", displacement 10,400 tons 1906
Hull 170 – length overall 474'6", displacement 16,670 tons 1914
Hull 261 – length overall 572'6", displacement 29,000 tons 1921
Hull 475 – length overall 628'0", displacement 34,145 tons . . . 1949
Hull 510 – length overall 707'0", displacement 49,450 tons . . . 1954

The Last Word in oil transportation

Oil transportation has come a long way since 1906, when Newport News delivered their first tanker. The advance becomes obvious when you look at the type Newport News is building today. Designed to carry 336,000 barrels at a speed exceeding 17 knots, the first of these huge ships will be commissioned in 1954.

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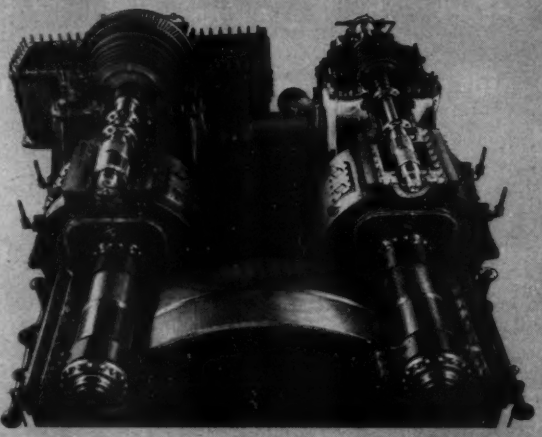
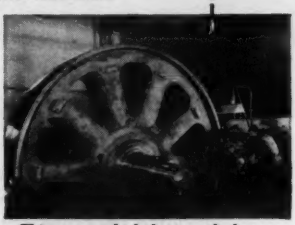


Here is a test floor view of a typical De Laval 13,750 shp main propulsion unit, one of seven built for a new super-tanker fleet. The gear elements of this unit were completely shaved for better tooth surface finish and more accurate tooth form. Since 1949, De Laval has pioneered in the shaving of bull gears and their mating pinions for main propulsion units. This is another De Laval engineering *first* which helps provide more dependable and efficient power for America's ships.



This unretouched photograph shows a 30 ton, 170 inch diameter, 44 inch face width, 15,000 hp marine gear being shaved in the De Laval plant.

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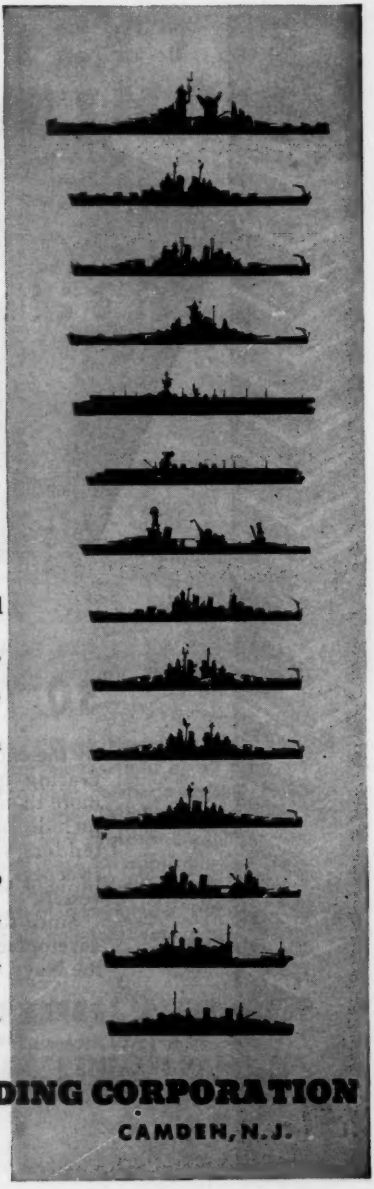

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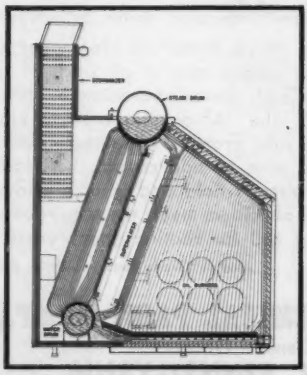

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REAR ADMIRAL F. W. SYLVESTER, U.S.N.

who has been elected President of the Society to fill out the unexpired term of Admiral Wallin whose change of duty in removing him from Washington has made it necessary for him to resign.

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JOURNAL

OF

THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

VOL. 65. AUGUST 1953. No. 3

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SECRETARY'S NOTES

THE FATHER OF THE BUREAU OF SHIPS

On 8 July 1953, Admiral S. M. Robinson, U.S.N., Retired, was formally recognized as the "Father of the Bureau of Ships." The title was announced by Rear Admiral Homer Wallin, U.S.N., Chief of the Bureau of Ships, on the occasion of the unveiling of a portrait of Admiral Robinson. Admiral Robinson was President of the Society in 1931, 1939. Admiral Wallin is now the President. Admiral Robinson's remarks on the occasion are of significance to naval engineers. They are printed for this reason and as a preview of a more detailed history, of that event, which is in preparation for publication in the JOURNAL.

Admiral Wallin—Ladies and Gentlemen—

To say anything on such an occasion as this is always difficult. However, Admiral Wallin has graciously offered to reproduce my remarks and send a copy to each ED Officer so I am going to take advantage of this opportunity to write a little history which would otherwise get lost in the course of time since few people know all the details of the events leading up to the formation of this Bureau.

I shall first cover the work of setting up the Bureau and then tell you how it was made possible to have a Bureau.

I will begin with Secretary Edison's decision to form the Bureau. He sat Admiral VanKeuren as Chief of the Bureau of Construction and Repair and me as Chief of Engineering down in adjacent offices and told us to get ahead with the job. I was given additional duties as Coordinator of Shipbuilding to cover the question of overall authority. Actually this was more or less of a gesture since Admiral Van and I acted as a unit throughout the whole time of organization. We had both anticipated a great deal of difficulty in welding the two Bureaus into one and we had considerable grounds for such apprehension since at the time the two Bureaus had been at sword's-point for a considerable time.

Now I have been wrong many times in my life but I do not recall any time when I was as wrong as I was in this case. Not only was there no difficulty in bringing about the amalgamation but it went so fast that Admiral Van and I were left far behind and were in a perpetual state of amazement. It is no exaggeration to say that the fusion took place immediately — it was more like a hydrogen-oxygen explosion than anything else. Organizations and sub-organizations were set up in some cases in a matter of hours — not days, weeks, or months. I do not mean to imply that the new Bureau sprang into existence full panoplied like Minerva from Jupiter's brain. Actually we were ironing out mistakes for many months but, in the meantime, the Bureau was functioning smoothly and efficiently and what a god-send that was because it allowed Admiral Van and me to spend most of our time getting a bill through Congress to legalize the setting-up of a single Bureau. And I may add that we certainly needed all the time we had.

Now of course there was a reason for all this. Everyone, both officers and civilians, were convinced it was a necessary thing to do and they all pitched in enthusiastically to do anything they could. I am not going to make any attempt to single out the individuals most responsible because to do so would certainly result in certain injustices and hard feelings. The real truth is that everybody in both Bureaus had a hand in it and there was no striving for personal position but only for the final result so it had to be a success. I have seen a good many miracles but this one stands out in my mind as the greatest.

Of course, during all this time of organizing and settling down Admiral Van and I were busy, both on the Hill and in the Navy Department, in getting a bill passed to transform us from a "de facto" to a "de jure" status. Here I had anticipated a lot of hard work but no great difficulty. I had good reason for this frame of mind since I heard no real opposition voiced either in the Navy Department or Congress. But again I was wrong — so very wrong.

Actually I despaired many times of ever having a Bureau. For one thing we got off to a bad start because the Navy Department loaded the bill with a lot of other "personnel" legislation and it was of a very controversial nature. The House Committee finally kicked out all this matter but it took weeks to do it and it left the bill saddled with the grandiose title of a "Bill to Reorganize the Navy Department." This title rose up to plague us at a later date when we were before the Senate. In fact, the bill was having such a rough road to travel in Congress, that a number of my friends tried to persuade me to separate it into two parts — one bill to cover the Bureau and another bill to cover the amalgamation of the personnel. I refused to consider such a proposal and in this case I believe I was absolutely right.

I knew perfectly well that enthusiasm is the most wonderful thing in the world but it can not be maintained at a pitch that amounts to a religious fervor. We would have been left with a Bureau composed of officers with entirely different methods of promotion, education, selection, etc., and it would eventually have destroyed the harmony so necessary to any Bureau. At any rate Admiral Van and I kept working away at the problem — spending most of our time on the Hill. The hearings lasted so long I was afraid there would not be enough paper to print the minutes. Each time we thought we had everything squared away some gentleman in high place would drop a monkey wrench in the wheels and we would start all over again. Fortunately the Chairman, Mr. Vinson, was a man with immense patience and he believed thoroughly in the bill.

Finally we got over all the hurdles, there seemed to be no opposition, and the hearings were concluded. Admiral Van and I took deep breaths, sat back and relaxed — till next morning Mr. Vinson called me up to say that two or three members had signed a minority report. Again some one had dropped a monkey wrench. The shock of this discouraged me more than anything that has ever happened. As you know, in the House, only a unanimous committee report gave the Chairman the right to get a special rule so that he could get his bill on the floor of the House. It looked like the end for that session of Congress.

Fortunately I had a good neighbor, John Crockett, Chief Clerk of the Senate. He knew more about getting legislation through Congress than anybody else in Washington. He gave me a lot of advice but the most important piece was to take my problem to Senator Walsh and this I did. The Senator told me that if I could get all the interested parties in the Navy Department to come before his committee and to agree to the House bill without changing a single word, he thought he could get the bill through the Senate.

This sounds simple but there were still some monkey-wrench throwers in the Navy Department and it required a positive order from the highest authority to bring them in line so that when we all went before Senator Walsh, the answers were all "aye." Senator Walsh's committee reported this bill out unanimously (all monkey wrenches having been expended) and it was placed on the Senate Calendar. It came up the following week but the grandiose title floored it. A Senator became alarmed and objected. But the smooth work of Senator Walsh persuaded the Senator to let it go over for another week and, in the meantime, he talked to the Senator and the following week it went through. These calendar bills all require unanimous agreement, of course.

Now the picture was changed completely and Senator Walsh's strategy became evident. Mr. Vinson had a club in his hand; here was his identical bill coming over from the Senate; he had held extensive hearings and the bill had been approved by a large majority. He could, and did, take the bill to the floor of the House where it passed without any objections. This time we really could celebrate and take time out for the first unworried moment in many months. At last we were legal. The bill passed just before the end of the fiscal year and this facilitated our change-over. I have often wondered what would have happened if this legislation had failed. I still shudder when I think about it. So much for the birth of the Bureau.

And now I would like to tell you why we have a Bureau. This time we can place the responsibility without any question or difficulty. The man who was responsible for our having a Bureau was Captain L. B. McBride — now unfortunately deceased. In his later years he was pursued by ill-health but at least he had the satisfaction of seeing his life's dream come true. I knew him well; we were respective heads of the Design Divisions of the two Bureaus for many years and I speak from an intimate knowledge when I tell what he did.

From the time when he was a young Lieutenant he started preaching the doctrine of a single Bureau. Of course, few people paid any attention to him most of the time. But he was a most

persistent, persuasive talker; also he was very bright and very popular. As the years went by, opportunities seemed to arise that offered some hope and he was always "Johnny-on-the-spot" with his plans but they always went wrong and it finally began to look as if Mac would never make it — especially since his health had become steadily worse. But I am sure that Mac never really gave up hope and finally his opportunity really came and he grasped it so quickly, so firmly and so completely that it never had a chance to get away.

As is always the case with successful plans, there have to be some favoring elements and this time he had quite a number. First, we had a strong Secretary of the Navy, Mr. Edison who had ideas of his own and had the courage to put them into effect. Second, the Secretary had the greatest confidence in Captain McBride although he had known him for only a short time. Third, the Secretary was tired of the squabbles between the two Bureaus and had made up his mind to do something about it at the first opportunity. Fourth, there had come about a considerable change in the attitude of mind of the whole Navy Department on this subject. In other words, the time was ripe and it only needed a man with imagination and boldness to do something about it and certainly Mac was not lacking in either of these qualities.

When some criticism arose in regard to the design of certain of our destroyers, the Secretary thought this gave him an excuse to do something about the two Bureaus and he proceeded to act. He set up a committee to recommend a plan for merging the Design Divisions of the two Bureaus. He undoubtedly thought he could do this by administrative action and that no legislation would be required. He appointed Captain McBride, Admiral Cochrane, Admiral Lee on the committee and made me the Chairman of it. Now Mac had not the slightest intention of letting this opportunity get away from him and Design Divisions were furthest from his thoughts. He believed the time had come to realize his life's dream and he lost no time in carrying it out.

I am perfectly certain that the day we met he had his plans all fully perfected but he said nothing about them. We discussed the problem of a common Design Division at great length. In fact we worked long hours because the Secretary was in a hurry. So was Mac. In order to lose no time, we continued our discussions at luncheon but after two or three days when I announced an adjournment for luncheon, I found the other three members all had some excuse for not going out so I went out by myself. If I had been psychic I am sure I would have realized that something was up because the members' excuses seemed rather thin after I had looked back on them. At any rate when I returned, I found

that Mac had held a caucus and proposed that we recommend a complete amalgamation of the two Bureaus; his reason for excluding me from the proceedings also became apparent. He proposed that I should be made Chief of both Bureaus pending legislation to unite them. He further proposed that we proceed immediately to see the Secretary and make these recommendations.

Now there was a reason for all this haste. Mac knew there would be some opposition and that it would build up with time making the problem much more difficult if not impossible of solution. It took me some minutes to recover from my astonishment and I tried to beg off from the job. I had a legitimate excuse. My health was not as good then as it is now and I did not know whether I would be able to stand up to the job. I had no illusions as to what was involved in carrying out this scheme. But Mac was a man possessed; he brushed aside all arguments and gave me a lot of "soft soap" about being a compromise selection — a sort of half engineer-half constructor. I took all this with a large grain of salt as I had been used to Mac's Irish blarney for many years, but the really deciding fact was that there was not time to search for some man who would be satisfactory to Mac so I agreed.

We immediately marched up to the Secretary's office and Mac laid the whole thing before him. I am sure the Secretary was as much astonished as I had been and his first remark was — "You have exceeded your precept, haven't you" A gross understatement if I ever heard one. However if he had known Mac as well as I did he would have realized that precepts meant very little to him. We harassed the Secretary for several hours and it was finally agreed to go ahead with the plan and immediately at that. He sent for the Judge Advocate General and told him to make up two Commissions for me to be sent to the President and we struck the first snag. The Judge Advocate General said this was illegal. That did not bother Secretary Edison very much. He had become enthusiastic and promptly solved this problem by giving me additional duties as Coordinator of Shipbuilding — a position the Secretary held himself at that time. That, of course, solved any questions of overall authority. Actually this was more or less of a gesture as Admiral Van and I worked as a unit from the very first. So two Commissions were made out for two people and Admiral Van and I started on the long, hard trek to getting legislation creating a Bureau.

Now I suppose many people had, from time to time, thought it would be a good thing to merge these Bureaus but the fact is that nobody did anything about it. It required a man of vision, imagination, and courage to bring it to pass. That man was Captain L. B. McBride and I sincerely hope that all ED Officers will always remember this, will honor his memory and take such steps that our younger ED Officers will be brought up to revere his memory.

FINANCES

The Society has reached a point where serious consideration must be given to the intriguing but annoying subject of finances—money.

Several years ago the Council decided that the JOURNAL should be expanded and, if possible, improved, both as to format and content. This led to the authorized expenditure of more money than was received. Only in 1952 (last year) was a condition of balance restored. A very slight dollar excess was attained. This was done by using the size of the JOURNAL as the determinant of profit and loss. That is simple. By reducing the number of original articles accepted, by printing fewer illustrations, and by reprinting a smaller number of articles, variations in cost can be met so that the overall operation of the Society may be kept out of the red.

One of the elements in this financial manipulation, at the beginning was submitting to the membership a proposal for an increase in annual dues. This increase of 50 percent to $7.50 was approved and is the only such increase in the 65 years of the JOURNAL's and the Society's existence. In spite of gradually (not always so gradual) increased cost, the Council has resisted suggestions that further increases in dues should be made. Very few societies today could exist with dues only 50 percent higher than in 1888 and it is a rare publication that contains twice (or more) the content at a selling price of only one a half times that of the final years of the nineteenth century.

There are five immediate factors which have now arisen almost simultaneously to aggravate the situation. These are:

a) A recent substantial increase in printers' wages which will increase the cost of printing the JOURNAL by about 7 percent.

b) A prospective increase in mail rates which may increase distribution costs considerably.

c) The need for improved offices which may increase the cost of rent several hundred percent. Few members may know that for its first 60 years the Society had adequate offices, rent-free.

d) The prospective retirement of the Clerk of the Society (this is not set but is inevitable in the near future) will, from preliminary inquiries, increase the Society's payroll by as much as $7,500. This is nearly $3.00 per member.

e) Annual subscriptions after 1 July 1953 will be about 20 percent less than they have been recently.

There can be no doubt that a change of some kind must be made. There are two practical methods of assuring that the Society remain solvent. The first of these is to continue to use the size

of the JOURNAL as the means of meeting increased costs. The other is to increase subscription and advertising rates and annual dues substantially.

This matter will be thoroughly studied by the Council during the Summer. It will be the principal matter on the Agenda of the annual meeting in October. Final decision will be largely in the hands of the members since there can be no increase in dues without a change in the by-laws.

This preliminary notice is written to invite comment and suggestions and to alert members to the importance of the 1953 annual meeting which will be held in Washington in October.

MEMBERSHIP

Every year, at the time of the Annual Banquet, a perennial misunderstanding becomes more prominent. The Society does not have company memberships. The only memberships are Naval, Civilian and Associate and each of these must be held by an individual who possesses the qualifications which are set forth in the by-laws. The only action which can be taken in the name of a company is to advertise in the JOURNAL and any reputable company's advertisement will be welcomed.

A MEMBER IS HONORED.

Mr. George W. Codrington, who retired early this year as a vice-president of General Motors Corporation and general manager of the Cleveland Diesel Engine Division of General Motors, was recently elected to the post of honorary chairman of the Diesel Engine Manufacturers Association. This is the first time such action has been taken by the DEMA, and is a tribute to Mr. Codrington's many outstanding contributions to the diesel industry.

Mr. Codrington has been a member of ASNE since 1940.

COMMENT

The following letter has been received:

Dear Editor:

You are invited to comment on the article by Mr. Karpow, the translation of which was published in your valuable magazine.

This article must be regarded rather moderate from the point of view of Soviet morale. Mr. Karpow was modest enough, as he avoided mentioning the names of several well known Russian scientists, who were not happy to die before 1917: Mr. Karpow cannot be excused by failure of his memory.

Contributions of such men as Joukovsky and Mendeleev are without any doubts. It is surprising, however, that Mr. Karpow was not orthodox enough, as he did not mention the extraordinary

merits in naval architecture of Stalin, the "greatest genius in the history of the mankind", as stated in the volume 10 of the Big Soviet Encyclopedia, new edition 1952. We must be anxious, that Mr. Karpow is already executed for such an inexcusable negligence.

The whole article resembles navigation in a fog, when sailor can see few near-by objects only, but no horizon!

I would like to add a small historic fact to the references, introduced evidently by the translator:

In 1741 the queen of Prussia honored L. Euler by inviting him to dinner. She was concerned that Euler was extremely silent. Euler explained: Your Majesty, I returned from Russia—a country, where people who speak, are hanged!

Sincerely yours,

DR. STEPONAS KOLUPAILA
Prof., University of Notre Dame

AWARD BY A MEMBER

It was previously announced that Captain Carl J. Lamb, USNR, had offered a membership in the Society. The photograph shows Captain Lamb making the award to Ensign Isaac M. Singer, Jr., USNR, who won by standing first in mechanical engineering at the Rice Institute, among those midshipmen first class who accepted commissions.

Captain Lamb has been outstanding in his interest in the Society. He has been a frequent contributor to the JOURNAL and a persistent recruiter of new members to the Society.

ADMIRAL S. M. ROBINSON, U.S.N., RETIRED
PRESIDENT A.S.N.E. 1931, 1939

REAR ADMIRAL HOMER N. WALLIN, U.S.N.
PRESIDENT A.S.N.E. 1953

THE DEVELOPMENT OF ATTACK AIRCRAFT CARRIERS*

LT. COMMANDER S. R. HELLER, JR., USN

THE AUTHOR

was born in Norfolk, Va., in 1920. He was graduated from the University of Michigan with the degrees of B. S. E., in Naval Architecture and Marine Engineering and in Mathematics. Following graduation he was employed by the New York Shipbuilding Corporation. On entrance in the U. S. Navy in 1942 he was ordered to the Norfolk Naval Shipyard and assigned to carrier construction. After World War II he was ordered to the Massachusetts Institute of Technology for postgraduate instruction resulting in the degrees of Naval Engineer (1950) and Doctor of Science in Naval Architecture (1951). Since that time he has been designated for Engineering Duty only and assigned as Assistant for Aircraft Carriers, Hull Design Branch, Bureau of Ships.

INTRODUCTION

As we prepare to enter the second half century of powered flight, it is appropriate that we pause and take stock of the naval application of the Wright Brothers' "interesting toy." Both the commercial and military phases of aviation have and will continue to be covered with meticulous care, so that only a few words are necessary to indicate the fantastic growth of the airplane. In fifty years of commercial aviation we have seen distances appear to shrink with more rapid travel, with faster mail and freight service, and with ease, comfort, and safety not thought possible. Today, fifty years after the first flight, we have more luxurious accommodations than George Pullman ever dreamed of—and the Pullman car was born fifty years after Peter Cooper's first locomotive ran.

In the same fifty years military aviation has developed apace. Although the military potential of powered flight was recognized at the outset, the far-reaching implications were initially slow attaining maturity. Artillery range and reconnaissance were extended a hundredfold. As a result, methods of warfare have been completely revolutionized. No longer is the naval fleet arrayed in its classic battleline with the majestic dreadnaught, the cynosure of all eyes. Now the queen of the fleet is the aircraft carrier.

* The development of the escort carrier type is adequately presented in (1) and this type is not considered in this article.

Note: Numbers in parentheses refer to Bibliography.

ATTACK AIRCRAFT CARRIERS

HISTORY†

History records that Eugene Ely first flew an airplane from a platform on the deck of the heavy cruiser USS *Birmingham* on November 14, 1910—less than seven years after the first successful flight by the Wrights. Some two months later, on January 18, 1911, the same Ely landed a plane on the deck of the armored cruiser USS *Pennsylvania*. A month later, Glenn Curtiss landed his seaplane near *Pennsylvania* and was hoisted aboard. The airplane has passed its naval feasibility tests, but it was still just the interesting toy. Simultaneously, Pegoud, the French aviator, was conducting similar experiments. The British followed in 1917 with tests aboard HMS *Argus*. At the close of World War I all major naval powers were seriously at work including aircraft in both their offensive and defensive schemes of operation.

In the United States, conversion of the collier *Jupiter* into our first aircraft carrier USS *Langley* was undertaken. At the same time the British were incorporating the lessons learned from *Argus* into HMS *Hermes*. Even as these pioneer carriers were being readied for service, the diplomats sat down in Washington to control the struggling infant along with other combat units of the fleet. The 1922 Washington Treaty Limiting Naval Armaments imposed the following restrictions:

a. Article VII. Total Standard tonnage of aircraft carriers allotted the various contracting powers was:

1. United States—135,000 tons
2. Great Britain—135,000 tons
3. Japan—81,000 tons
4. France—60,000 tons
5. Italy—60,000 tons

where a ton was defined as "2240 pounds"; and standard displacement as "the displacement of the ship complete, fully manned, engined, equipped ready for sea, including all armaments and ammunition, equipment, outfit, provisions and fresh water for crew, miscellaneous stores and implements of every description that are intended to be carried in war, but without fuel or reserve feed water on board."

b. Article IX. No aircraft carrier shall exceed 27,000 tons standard, except each contracting power may have two, not exceeding 33,000 tons standard and may, to effect economy, use ships which would otherwise be scrapped. (Author's note: To permit the United States to continue with *Lexington* and *Saratoga*.)

c. Chapter II, Part 4. An aircraft carrier is defined as a vessel of war with a displacement in excess of 10,000 tons standard, designed for the specific and exclusive purpose of carrying aircraft. It must be so constructed that aircraft can be launched therefrom and landed thereon.

The limitations thus imposed on aircraft carriers were not overpowering, per se, but Article VII definitely hamstrung the normal development of a device that was then imperfectly understood. The definition of an aircraft carrier gave rise to fitting "flying-on decks" in battleships and cruisers as a subterfuge to avoid the "specific and exclusive purpose of carrying aircraft."* The weight limitations focused attention immediately on the necessity of careful design and weight control. With the completion of *Lexington* and *Saratoga* there were available to the United States only 69,000 tons standard for the carrier program. Immediately the controversy over the relative number and size of future carriers flared, see (3), (4), and (5). The naval aviators were of the opinion that a larger number of

† Much of this information is abstracted from (8), (9), and (10).

* See (2) for detailed account.

small carriers, 5 ships at about 13,000 tons standard, were preferable for the following reasons:

1. With more ships, there could be more deck space, more take-offs, and more landings per ton.
2. Protection by segregation.
3. Smaller target, hence less vulnerable.
4. Small carriers could handle the required number of planes.

On the other hand, the naval constructors favored the larger ship, 4 ships at about 17,000 tons standard, in order to achieve a better balanced design. The reasoning followed these lines:

1. Speed is essential, but the horsepower differential, and thereby the weight differential, is small.
2. Same number of arresting engines, elevators, and other aeronautical features will be required for any carrier.
3. More of the standard displacement of a larger ship can be put into protection, provided speed and aeronautical features remain the same. It should be noted the *Ranger,* the next American carrier authorized, was designed at 13,800 tons standard.

After the design of *Ranger,* there remained but 55,200 tons standard available for aircraft carriers. Although no significant advance had been made in plane development in the meantime, a re-examination of the tactical use of naval aircraft plus lessons learned in plane handling and recovery on the fleet carriers led to the conclusion that duplicates of the *Ranger* were not desirable. Accordingly, new studies were made to include more planes, gasoline, and ammunition to increase the scope of aircraft operations. The resulting design required 20,000 tons standard. Two such units were ordered: *Yorktown* and *Enterprise.*

The design of *Wasp* was based simply on getting the maximum aeronautical ability into the remaining aircraft carrier tonnage—15,200 tons standard. A ship of this size was naturally not a logical step in the orderly development, but was actually an honest effort to make the best of a bad bargain. When *Wasp* was actually built, it had a standard displacement of 14,700 tons, leaving 500 standard tons as the unexpended balance.

Following the design of *Wasp,* the London Naval Treaty of 1936 became effective. The provisions of this treaty with regard to aircraft carriers were:

1. Maximum standard displacement of aircraft carriers was reduced to 23,000 tons. (Author's note: Apparently at British insistence).
2. Maximum gun size was set at 6.1 inches.
3. No more than 10 guns larger than 5.25 inches.
4. Definition of an aircraft carrier was modified to place emphasis on "ability to operate aircraft at sea."

At the outbreak of hostilities in Europe in 1939 and in light of the announced policy of Japan to terminate her contract in the 1922 Washington Treaty and the later London Treaties, the United States took one quick look over its shoulder, ordered *Hornet,* a duplicate of *Yorktown* and *Enterprise* as a matter of expediency, and set out to design its first aircraft carrier without treaty restrictions. The design which resulted in the renowned *Essex* class was completed in 1941 with a standard displacement of 27,100 tons. An analysis of the performance of *Essex* and her sisters during World War II leads to the inevitable conclusion that here, at last, was a truly balanced design. In spite of bombing, strafing, torpedoing,

and kamikaze attacks not one of *Essex* class was sunk—a truly remarkable record. And, throughout this constant enemy effort to blunt fast carrier task force action, *Essex* class continued to deal its devastating blows in support of landings, neutralizing strong enemy outposts, and even daring to control Japan's home waters. The dry statistics of planes shot down, tonnage sunk, and fortifications or vehicles neutralized, tell the story, but this has all been reported elsewhere. At last, the attack carrier had been developed and with it the daring new naval strategy and tactics to exploit its potentialities to the utmost.

As a result of early war experience, however, the design of *Midway* placed greater emphasis on protection than had heretofore been used. In addition, greater quantities of planes, gasoline, and ammunition were desired. Great strides in plane improvement were taken as the military situation demanded; consequently, a much larger ship, 45,000 tons standard, was the result. Unfortunately, for the evaluation of improvements incorporated in *Midway* class, no ships had combat experience.

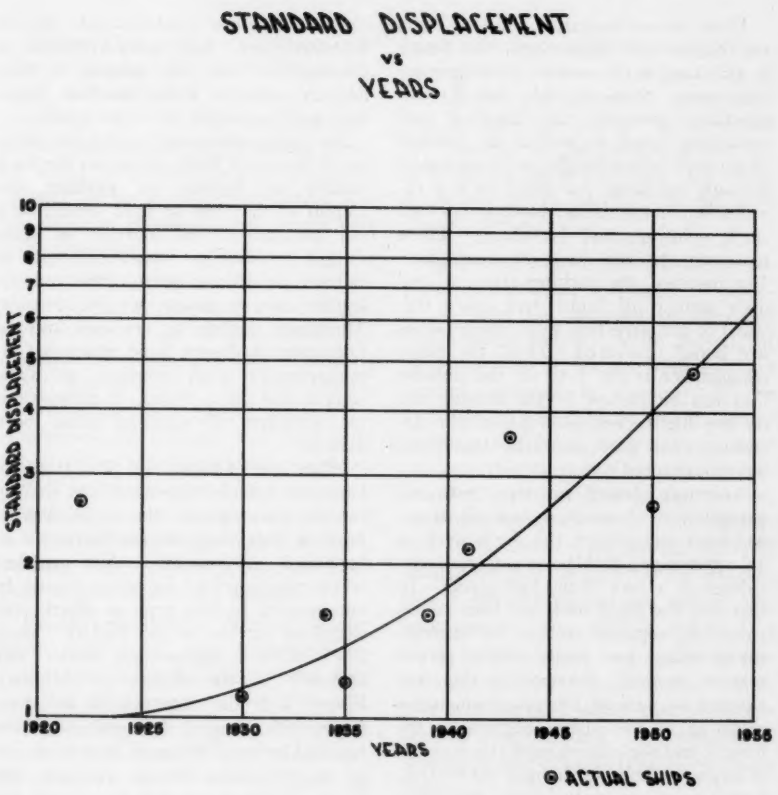
Immediately after World War II, jet propelled aircraft became available. These voracious consumers of fuel dictated greatly increased fuel quantities. Because of their high speed, the required catapulting and arresting facilities also increased. In addition, the heat and velocity of the jet blast posed new problems for protection of personnel and embarked aircraft. In 1948, design was started for *United States,* 70,000 tons standard, but the design was never completed when budget limitations in 1949 deleted the ship from the building program. In 1950, modifications to the wartime *Essex* class were undertaken to incorporate these desired changes. In 1952, *Forrestal* class, 60,000 tons standard, was designed, and their construction started. This design, the first completed in the post-war period, incorporated the proven features of *Essex* class, the desirable features of *Midway* class, the modifications required for jet plane operation, plus allowance for aeronautical growth. Figure 1 shows the growth in displacement versus time.

DEVELOPMENT OF SPECIAL CARRIER FEATURES

It was recognized quite early in carrier development, (3) that the naval architect's basic problem in aircraft carrier design was space, more than weight. The vast quantities of aviation fuel and ammunition and the tremendous expanse of hangar area for aircraft servicing and parking are typical of the space requirements. Space, however, is not the sole problem of carrier design.

DISPOSAL OF FLUE GASES

Early in the design of *Langley,* it was realized that the time-honored centerline smokepipes were incompatible with the aviation requirements of a clear hangar and an uncluttered flight deck. The solution in *Langley* was a set of hinged ducts set at the flight deck edge. A similar solution was followed in *Ranger* where six such hinged pipes and dampers were installed that permitted selective discharge from either side, in either the up or down position,



depending on the nature of operations. In *Lexington* and *Saratoga,* however, the smokepipes were incorporated within an "island" where air, ship, and fire control functions were also located. The island method has been continued in use up to this time. For the first time since the design of *Ranger* in 1930, the 1952 design, *Forrestal,* does not include a fixed island. Hinged smokepipes and dampers permitting selective discharge similar to *Ranger* are provided. A small island to house the air and ship control functions will be fitted in *Forrestal* with the retractable feature incorporated to permit a flush deck during air operations. It is interesting to recall that a similar plan was featured in the design of *Ranger,* but later considerations of ship control forced the adoption of a small fixed island. To prepare for such an eventuality, space has been reserved for an alternate fixed island in *Forrestal.*

FLIGHT DECK

From the aeronautical point of view, the bigger the flight deck, the better it is. Length, however, is of greater importance than breadth, for it substantially governs the landing and launching speeds as well as the number of aircraft which can be accommodated. Broadly speaking, the flight deck is divided into three areas: landing (arresting), spotting, and launching. These divisions are not, however, restrictive. For instance, the parking area can and does include all flight deck space forward of the arresting gear when planes are being recovered. Thus, the plane complement is the total of the number that can be parked in the hangar and on the flight deck forward of the arresting gear plus one (the last plane being recovered).

American design practice, with the exception of *Lexington* and *Saratoga,* has been to consider the flight deck as an appendage; that is, it was not considered as a part of the hull girder. To that end, the flight deck had been segregated into separate sections by incorporating expansion joints which permit relative motion. Presumably this was adopted because of the requirement for warm-up of the piston engines in the hangar and the concomitant requirement of large openings for hangar ventilation. Large openings in the sides, naturally, are not compatible with the use of the sides for shear webs when the flight deck is the upper flange of the hull girder. Consequently, American flight decks were designed solely to withstand the local loads of landing or parking. British practice, on the other hand, was to make use of the flight deck as a primary structural member. Not until 1952,* when jet operation, which required no warm-up, became predominant, did the U. S. Navy again design a flight deck for both local loads and hull girder action. It is obvious that special attention must be paid to the location, size, and reinforcement of openings in the side plating if they are to perform their function properly as shear webs of a box girder.

As a consequence of basing the structural design of flight decks on the local loading of landing or parking, the weight of material so used should be a fair measure of the increase in plane weight. Stability considerations, of course, would not permit the concentration of so much weight topside. Therefore, continuing research and refinements of theory have proceeded simultaneously with increase in plane weight and, as a result, disproportionate amounts of material have been avoided.

With the advent of the Japanese kamikaze attacks, attention was sharply focused to armoring the flight deck to prevent such wholesale conflagrations as happened in *Franklin* when attacked while refueling and rearming planes. In anticipation of this type of attack plus excellent service of the British "hard-top" carriers, flight deck armor was included in the design of *Midway.* Faced with the requirement of large flight deck weights for protection and assisted by the deletion of hangar warm-up as jet planes became available, the U. S. Navy proceeded to design the flight deck of *Forrestal* as the upper flange of the hull girder to take advantage of material already present.

With the advent of jet aircraft, devices for protecting personnel, spotted aircraft, and the deck itself, were obligatory. Ships operating jets now are fitted with some type of deflector to guide the blast upward and outboard. Further research into this problem is continuing. Non-skid surfaces, as always, are required; but, jet heat and blast have harshened the requirements for these materials.

* The partially designed *United States* whose design was started in 1948 was intended to have the flight deck as a part of the hull girder, but the design was never completed.

CATAPULTS*

Although catapults for launching missiles of war are almost as old as war itself, the adaptation of this primitive instrument of war for launching airplanes antedates successful heavier-than-air flight. Professor Langley used coil springs during his experimentation and the Wright Brothers used cables and falling weights.

The first airplane catapult for the U. S. Navy was developed at the Washington Navy Yard in 1912 under the direction of Captain W. I. Chambers, USN. Compressed air was the medium for obtaining the required force. The compressed air catapult was used quite successfully for launching seaplanes both from barges and combatant ships. Refinements of the design were effected to stop the catapult cars, and, as a result, the improved compressed air catapults were installed in *Langley*.

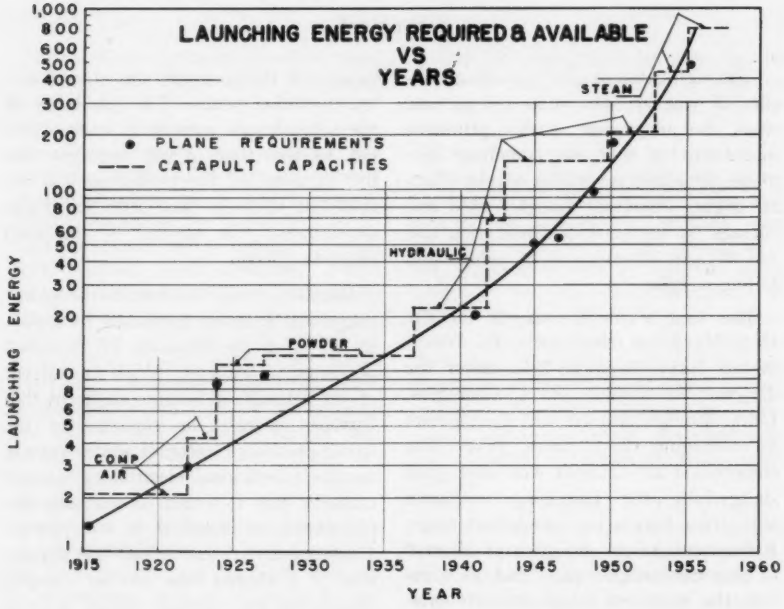
Simultaneously C. L. Norden, of later bomb sight fame, was developing flywheel type catapults which were later installed in *Lexington* and *Saratoga*. Although the launchings made by this flywheel type catapult were successful, the catapults were removed from the ships so fitted since they were equipped only for launching twin float seaplanes and were seldom used. Meanwhile, powder actuated catapults were being developed. Powder was first suggested as a replacement for compressed air by Lt. Comdr. Hamlet, USCG. In early 1922, an experimental catapult was tested. The immediate success of the powder catapult was indicated by its adoption in all type fleet units handling aircraft.

Late in 1934 studies were undertaken to provide the necessary launching force by hydraulic means. The feasibility of the scheme was proven in early 1935, but, by that time, it was apparent that the capacity of the prototype was insufficient to keep pace with the rapid developments in aircraft to be used aboard carriers.

Successive improvements to the hydropneumatic catapult increased its capacity to meet the demands of increased performance aircraft. With the advent of jet aircraft, it became apparent that further increase in capacity of the hydro-pneumatic catapult would require so much additional electrical generator capacity that it would be virtually impracticable to install it in any carrier. Consequently, research into the adaptation of a slotted tube powder catapult similar to the German device used to launch the V2 rocket was begun. Simultaneously, the British scheme of using a slotted tube steam catapult was considered. Recently, the steam catapult was adopted when that prototype became available first. The relation of launching energy with time is shown in Figure 2.

Locations of catapults, arresting gear, and elevators are closely related and must be carefully studied as a single problem. Early carriers were designed to have athwartship catapults fitted on the hangar deck. When increased plane size would have made side openings extremely large, this scheme was abandoned. Only the first two of *Essex* class were so fitted and the hangar deck catapults were removed shortly after completion.

* Abstracted from (6).



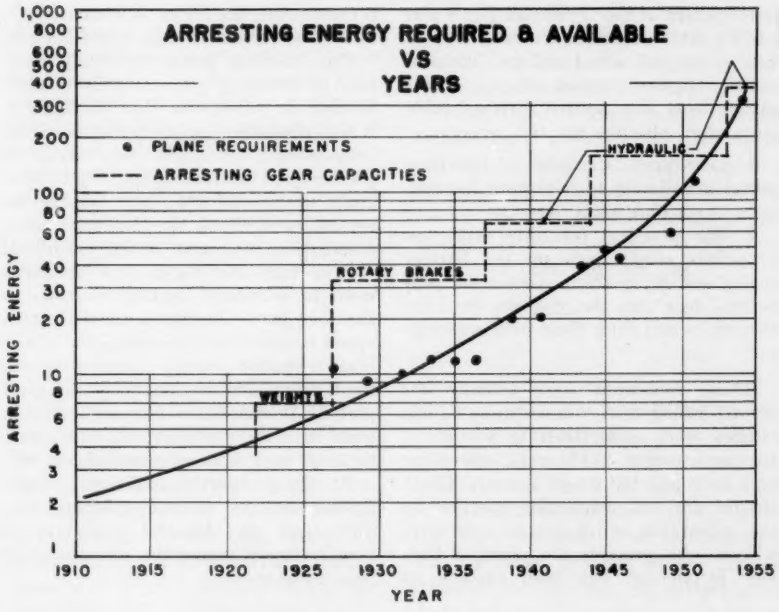
ARRESTING GEAR*

In 1911, when Ely landed aboard *Pennsylvania,* all the basic essentials of arresting gear were present. A series of 22 athwartship wires to which were attached two 50-pound sandbags (one at each end), held by supports some 12 inches above the deck, was provided. The airplane was equipped with three pairs of hooks to engage the wires. Arresting was accomplished by dragging the sandbags. In the 42 years that have passed into history, many developmental changes in arresting gear have been adopted, but the basic principles remain unchanged.

In 1922, when *Langley* joined the fleet, the 50-pound sandbags had been replaced by a series of 830-pound weights and the number of wires reduced to five. In 1927, the *Lexington* and *Saratoga,* the wires were provided with rotary brakes, one at each end. This significant change was fathered by C. L. Norden and T. H. Barth. This arrangement, however, provided no interconnection between brakes and, consequently, off-center landings did not load the brakes equally. In addition, frequent part replacement and complexity of tensioning pointed out other disadvantages of the unit.

The need for a simpler and smoother energy absorber, which could accommodate off-center landings, brought about the development of hydraulic type arresting gear. The original hydraulic

* Abstracted from (7).



design (1928) was a *tension-ram* type unit. The heavy structural foundations required, leakage problems, and the requirement of two units per wire were inherent disadvantages. Developments started to overcome these difficulties resulted in a *compression-ram* type wherein the ram displaces fluid into an accumulator. Retrieving of the cable is then accomplished by using the air compressed above the fluid in the accumulator to force the ram back to the ready position. Units of this type were installed in *Ranger* and back-fitted in *Lexington* and *Saratoga*. Many refinements to this type have been made, as time passed, to increase the capacity, but the basic principles are still in use today. Figure 3 shows the relation of arresting energy to time.

In addition to cross-deck pendants for arresting planes in normal landings, some means for stopping wild or errant aircraft were required to protect personnel and parked aircraft. This requirement led to barrier design. The most extensively used barrier consisted of a pair of cables supported above deck to engage the engine cowl and main wheel struts and which were attached to an energy absorber. The original barrier energy absorber was a broach-type device. Energy absorption was controlled simply by varying the thickness of the ring in which the hole was to be enlarged. With the development of hydraulic arresting engines it was logical to make use of these machines to absorb the energy. Accordingly, a reeving arrangement was devised to permit their employment for this purpose. Multiple barrier installations were provided for additional safety and standby purposes.

This barrier arrangement was satisfactory and continued in use until the

development of the Grumman *Tiger Cat* (F7F) which featured a nose wheel in lieu of the tail wheel and two reciprocating engines instead of one. This plane made the normal barrier cable suspension obsolete for two reasons:

1. Inadequate strength in the nose wheel installation to withstand the necessary retarding loads; and
2. The practical certainty that twin propellers would pick up the barrier cables and wrap them around the propellers, tear out the engines, or snap the cables and fling them into the cockpit.

These conditions were actually observed during tests. Immediately design studies were undertaken to provide a barrier which would be satisfactory for both nose and tail wheel aircraft. These studies are still continuing sparked by the appearance of jet aircraft with nose wheels. At present, the multiple barrier installation has been adapted to accommodate the older tail wheel type as well as the newer nose wheel variety.

One startling factor regarding location of arresting gear must be touched briefly. In pre-World War II carriers, it was common practice to duplicate the conventional aft flight deck array in the forward portion of the flight deck. This, of course, not only doubled the topside weight of the arresting gear installation, but also forced additional weight into the flight deck structure itself to withstand landing reactions in the fore part. Furthermore, the astern speed required for bow recovery of aircraft required special features in the main propulsion machinery. In the early part of World War II, when arresting gear capacity was increased once again to keep pace with development of aircraft, the prospective additional weight burden and its adverse effect on stability plus the doubtful advantage of bow recovery caused the elimination of this requirement.

ELEVATORS

The number, platform size, and capacity of elevators are purely functions of the planes to be handled. The locations of the elevators must be carefully considered in conjunction with arresting gear and catapults to provide an integrated plane handling process. Early carriers were fitted with inboard elevators; that is, platforms completely surrounded by decks either in the up or down position. This was probably caused by the use of plunger actuated platforms. This type of elevator mechanism was perpetuated up to *Midway* when cable lift platforms were adopted. Since *Midway,* all new elevators have been of the cable lift variety and the service experience has shown vast improvement over the older plunger type.

It has long been recognized that the inboard elevators with their pit requirements imposed severe structural hardships on ships designed with the hangar deck as the upper flange of the hull girder since a discontinuity has been introduced. The pit also served as a "catch basin" for spilled gasoline with a resultant increase of hazard. Similarly, the presence of the opening in the flight deck imposes a structural penalty on those ships in which the flight deck is the upper flange of the hull girder. In addition, the plunger type elevator is more susceptible to shock than are the cable lift types. Furthermore, the plane handling capacity of inboard elevators is limited by the physical dimensions of the opening. Pit space and similar gallery deck space in way of the elevator opening are direct losses in highly desirable and usable space. In view of the numerous disadvantages inherent with the inboard elevator of plunger actuation, it is not difficult to see why

deck elevators of the cable type were so attractive. The inherent undesirable features of a deck edge elevator, of cantilevering large weights, the possibility of immersion of the platform and supporting structure, and the presence of large holes in the side structure were overcome by use of trusses for support of the platform and intensive research into reinforcement geometry and location of the openings. From the humble start with an experimental installation in *Wasp*, the deck edge elevator gained favor in increasing amounts. One such elevator replacing the midship centerline elevator was fitted in each of *Essex* (although the original design did not include one) and *Midway* classes; an additional deck edge elevator was gained during modifications of *Essex* by eliminating the aft inboard elevator; and, finally, all four elevators in *Forrestal* are of the deck edge variety.

GASOLINE

Not only has the quantity of gasoline to be stowed presented a problem, but the inflammable nature of the liquid and highly explosive vapor requires considerable attention for safety in stowage and handling. It has long been U. S. Navy practice to surround the stowage tanks with voids capable of being filled with inert gas. Initially, separate tanks of special materials, such as corrosion resisting steels, were used; but, basic research indicated that "built-in" tanks; that is, part of the ship structure proper, were entirely satisfactory and no special materials were required.

In order to limit the presence of the explosive vapor, salt water displacement was introduced. Float gauges, sensitive to change in buoyancy and thereby to the difference in density, were the first safety measures installed to prevent salt water from being pumped to the plane's tanks. Later, however, the "saddle" tank was introduced. This innovation, whose name comes from its geometry, was conceived for further safety. The concept is that of three separate structures:

1. Outer tank
2. Inner tank
3. Draw-off tank

Pump suction is always taken directly from the draw-off tank. Salt water is introduced into the system simultaneously and enters the outer tank first. The salt water automatically displaces gasoline from the outer tank and pushes it into the inner tank and thence, into the draw-off tank. Thus, the system is always full and the difference in density between salt water and gasoline automatically keeps the gasoline (without salt water mixed) moving upward and closer to the pump suction.

Service stations are required at both the flight and hangar decks for refueling planes prior to flight and defueling the remaining fuel after flight. Careful attention must be paid to their location to insure adequate coverage of the parking areas.

The remainder of the system, the piping between the pumps below and service stations topside, requires detail attention. By the use of double wall piping, the outer layer of which is inerted, the fire and explosion hazards are lessened. Pumping rates and piping sizes are of necessity closely related. Segregation capabilities of the system are directly connected to the damage control concept in vogue.

AVIATION AMMUNITION

The aviation ammunition carried by an aircraft carrier is directly comparable to turret ammunition carried by battleships and cruisers. As is pointed out in (3), bombing and torpedoing are comparable to heavy gunfire, and fighter plane ammunition to anti-aircraft fire. This item is the payload of a carrier.

Not only has the quantity of aviation ammunition grown, but the types have become more diversified. To the original group of bombs, torpedoes, and small caliber machine gun ammunition have been added mines, rockets, guided missiles, and even atomic bombs. As the speed of embarked aircraft increased, the geometry of the externally carried ammunition changed to decrease the drag at high speeds. Naturally, the volume for a given weight increased as the profile became streamlined. Thus, magazine space requirements grew somewhat for the same tonnage. The requirement of carrying more and more weight of ammunition caused a tremendous increase in magazine space.

Stowage, as in other ships, should be well protected. Hence, a centerline location behind both horizontal and vertical protection is indicated. The requirements of a clear hangar demands that encroachment on usable hangar space be minimized and obstructions be located well outboard. Thus, a Y-shaped flow of ammunition from magazine to hangar and flight deck is indicated. Furthermore, the ever present hazard of gasoline dictates a "break" in the ammunition train to avoid the flow of gasoline spilled on hangar or flight deck directly into the magazines. Because of the large space already required for magazines and the inert nature of fins, vanes, and other accessories, it has been standard practice to stow the explosive portions of ammunition behind protection and the inert portions outside protection. This separation of components requires that they be brought together, assembled, and thence transported to the aircraft. To accomplish this operation, space is required between the terminals of the "break" in the ammunition train. *But space is already at a premium.* Therefore, compartments to do double duty are required. Messing facilities lend themselves particularly well to portability; and thus are adaptable for dual use. Consequently, crew's messing and bomb assembly are designated for the same space, but do not take place concurrently. Since ammunition elevators, assembly areas, magazines, messing facilities, galleys, food service stations, provision storerooms, and refrigerated spaces are all interwoven in the complex network of mess lines and ammunition handling, the locations and quantities of these items must be firmed early in the design of a carrier.

FIRE FIGHTING

The tremendous offensive potential of attack aircraft carriers makes them prime targets. It is inconceivable that such targets can escape unscathed. This conclusion is borne out by the record of World War II. Having accepted the possibility and probability of damage, the designer is faced with the task of providing the best possible means of limiting such damage and preserving the ship. The damage control measures provided will normally follow standard surface ship procedure for all types of damage except fire. Fire aboard a carrier can become a conflagration in short order because of the large quantities of gasoline and ammunition stowed and handled. Refueling and rearming of

planes on the hangar and flight decks cannot be avoided, even though this procedure exposes the hazard to air attack. Accordingly, positive safety precautions and elaborate fire fighting equipment and techniques are required.

From the beginning, hangar sprinkling and water curtains were installed in recognition of the special hazards existing on hangar decks. Water curtains were designed to afford segregation by dividing the fire into small ones which could be extinguished more easily than a mass conflagration. Hangar sprinkling was originally provided to extinguish gasoline fires, but water has not yet accomplished this purpose. Hangar sprinkling, however, does serve two useful purposes in cooling the structure, thus minimizing structural damage, and preventing vapor explosions by cooling the upper layer of hangar space.

When saddle tanks for gasoline were adopted for the latter ships of *Essex* class together with double-walled piping, fixed fog sprinkling systems were installed in all spaces adjacent to those through which gasoline passed and those through which ventilation serving gasoline pumps room passed. Furthermore, explosion proof vent sets and isolated vent systems were provided for these spaces in order to lessen the hazard of gasoline vapors. The fixed fog system consisted of fixed piping with special water "fog" heads and connections for attachment of hose to fire plugs. The purpose of this special system is to cool ahead of the fire-fighting party in gaining control of a gasoline fire.

Chemical foam was the first improvement effected in extinguishing gasoline fires. These units were small, portable, and suitable for attaching to normal fire hose lines. Foam was produced by a chemical reaction between foam powder and water. Although this was a major step forward, there were two major disadvantages:

1. Insufficient capacity per unit; and
2. Malfunctioning of unit because of clogging of apertures and kinking of hoses.

In the early part of World War II, mechanical foam was adopted. This system uses a proportioner which mixes liquid foam directly into the water stream and is mechanically formed into foam at the nozzle. *Essex* class was provided with such a system. Continuous operation was assured by use of both sides of the proportioner. Better quality foam was achieved. However, insufficient capacity still existed. Research into foam manufacture continued, as extensive fire damage during World War II provided the impetus for substantial improvement. Unfortunately, a means of making foam that was superior to the proportioner system was not developed until after hostilities ceased. The development of the high capacity fog foam system was achieved shortly after World War II, however, and has been installed with continuing improvement in carriers since that time. The system is one of forced injection rather than venturi injection. Fire main water actuates a turbine driven, constant displacement, foam liquid pump which automatically insures the proper proportion of foam to water over a wide range of pressures. Capacity is attained by the provision of a large foam supply tank. Remote controlled monitors installed in the hangar area allow the fire to be fought prior to entry into the burning space. Entry is effected after a foothold has been gained. Final extinguishment is obtained by "mop-up" foam hose lines. Foam hose lines at the flight deck are also provided.

Conflagration stations for control of fire fighting in the hangar area were first provided in *Yorktown* and *Enterprise*. With the advent of the high capacity fog foam system, remote control of these installations were provided in the conflagration stations. Somewhat later, in *Midway*, blast doors to segregate the hangar area were provided.

Conflagration stations were then installed in each subdivision. Prior to World War II spare planes were carried triced up to the underside of the flight deck. When *Wasp*, *Hornet*, and *Yorktown* were damaged, fire fighting in the hangar deck area was severely handicapped where these planes fell. After these sad experiences, tricing of planes to the overhead was omitted.

Finally, fire pump capacity and piping design must be matched not only with the special features described above, but also with the magazine sprinkling and normal fire plug operation. Especial attention must be paid to segregation ability in order to provide for the possibility of piping damage during combat.

SPEED AND FORM

Since *Langley*, all attack carriers have been required to make at least 27 knots. This speed was required both for maneuverability and to provide wind over the flight deck, when there was no natural wind, to assist aircraft take-offs and landings. Even when catapults were improved, the speed requirements were retained, for aircraft take-off requirements grew faster than catapult launching ability. Today, speed is a basic factor for "fast" carrier task force action. Fairly high speed astern was formerly required in connection with bow recovery of planes. This high speed astern materially increased the problem of adequate rudder strength as well as complicating the machinery design.

High speed automatically requires fine entrance which in turn complicates the support of the flight deck. The wide flight deck and narrow waterline forward combine to force flare which is concave upward. Special attention must be paid to the shape in this area to prevent pounding and to assure a dry flight deck. This latter consideration has led to enclosed bows. The fine entrance may be compromised somewhat by space considerations, particularly in the forward end of the protected zone. In any case, abrupt changes of sections must be avoided to eliminate eddying.

Maneuverability and vulnerability to attack from the stern requires special attention to the after body. In particular, multiplicity and separation of rudders and propellers are required. Consequently, the stern must be designed around these obstacles with due attention given to propeller tip clearance, adequate rudder immersion, proper structural support of shafting and rudders, vibration, and space within the ship for steering gear.

Freeboard of the flight deck is intimately associated with all weather flight operations. Consistent with its structural support, the flight deck should be as far above water as stability considerations will permit. Past experience has indicated that 6% of the ship's length is a desirable minimum.

ARMAMENT

The basic concept of armament for aircraft carriers has changed greatly from *Lexington* and *Saratoga* to *Forrestal*. The battery of eight 8" guns in the older ships gave the impression that perhaps aircraft carriers would have to take their place in the battleline and perform artillery functions. With the passage of time, however, artillery requirements were removed and now only anti-aircraft fire is provided. Even the latter requirement is diminished, as task force experience is gained. The escort screen is relied upon for major

protection and the carrier itself provides only self-preserving coverage. The emphasis has definitely shifted, and properly so, to a maximum of aeronautical potential at the expense, if need be, of artillery.

CONCLUSION

The aircraft carrier has developed rapidly. Gradual development has not been possible as it was in the case of the battleship because the main offensive weapon of the carrier—the airplane—was but imperfectly understood; whereas the use of artillery and fortifications dates back centuries. Furthermore, legal quantitative and qualitative restrictions never existed in the infancy of the dreadnought. As aviation grows, so *must* aircraft carriers. The history of the development of aircraft can only tell us where we have been and, perhaps, point out where we might be heading. The point of diminishing returns may already have been reached; certainly the meteoric rise which is characteristic of the accompanying curves indicates that a plateau must be reached shortly or else shipbuilding facilities will no longer be adequate. Pessimism is, however, not warranted. Skeptics also scoffed at Scott Russell and *Great Eastern;* but steel nevertheless replaced wood as *the* shipbuilding material and ship size again grew. So it may be with us. Ships must and will keep pace with the aircraft they support.

ACKNOWLEDGMENTS

This paper is naturally not the product of a single person. The author desires to express his gratitude and indebtedness to: Mr. A. O. Van Wyen of the Aviation History Unit of the Office of the Chief of Naval Operations for furnishing background to the History section herein; to Mr. W. A. Aberg of the Carrier Branch of the Bureau of Aeronautics for furnishing information on aeronautical features and friendly guidance; and to Mr. G. E. Sieker of the Hull Design Branch of the Bureau of Ships for furnishing, from his vast store of design information and experience, little known and remembered facts of the early carriers, helpful research, and—above all—advice, counsel, kindness and encouragement.

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SO, YOU WANT TO BE AN INVENTOR

ACKNOWLEDGMENT

C. D. TUSKA, Director of The Patent Department, Radio Corporation of America, is the author of this article. It appeared in the March, 1953, edition of the "Journal of the Franklin Institute."

It is an appropriate time to talk about your aspirations to be an inventor because we have just observed the 500th anniversary of the birth of one of the greatest, Leonardo da Vinci. Although best known for great paintings and superb drawings of the human anatomy, Leonardo might have achieved lasting fame for his scores of brilliant inventions. Maybe you think that air-conditioning is an innovation of our times? Leonardo, history reports, built an air-conditioning unit for the boudoir of Beatrice d'Este, the wife of his patron, about the end of the 15th Century. Many people attribute the machine gun to Gatling or to Sir Hiram Maxim, but Leonardo had a couple of not-too-bad machine gun designs back in his day.

I recall going across a two-level bridge at Spuyten Duyvil, New York, a few times last summer and feeling thankful that the traffic was in one direction only. This summer when I leave Manhattan Island via the two-level bridge I'll remember that Leonardo proposed a two-level bridge—upper level for pedestrians and lower level for vehicles. Perhaps you could make a great invention by borrowing from Leonardo and devising, a simple cheap, and practical way to redesign a few of our city streets with a pedestrian level and a motorcar level. Two groups of our population would be eternally grateful, even if the idea lacks novelty.

If you want to be an inventor, you might use a few broad hints. Without even the slightest pretense of modesty, I think I am your man. My daily job has put me in a position of seeing not only hundreds of the brain children of some of the world's best electronic scientists and engineers, but thousands of the products of the minds of many enthusiastic "outsiders" who "want to be inventors." Every mail brings more ideas but rarely an invention, much less a patentable one. Why do so many people have an apparently irresistible urge to create inventions? What are some of the conditions that beget invention? I am going to take a careful look at the circumstances surrounding the birth of a few of the inventive creations of inventors well known to many of us. In doing so I may be fortunate enough to discover a few "rules for inventors" but at least I shall make observations that may be helpful.

If this were a dignified logical approach, you would expect me to define what I mean by inventor, invention, discovery, patentable invention, and per-

haps a few other terms of the patent profession. The astounding thing is that if I tried to define the terms, I would be rushing in where many of the great ones hesitate to tread. Even the most able of our judges have concluded that invention slyly eludes definition. I am content, for the present, to let it go at that because it won't help to say an inventor is one who invents. But it may help to look back at a few recognized inventors and how some of them came to invent or discover some of the things that made them famous.

Thinking that age might be a factor in invention I picked about a dozen and a half notable inventions that arrived during the 150 years following James Watts' steam engine. An even dozen of the inventors were between 27 and 35 years old when they made their important contribution. If you happen to be younger or older don't be impatient or discouraged. Marconi made one of his great wireless contributions at age 21 according to my calculations; McCormick came along with a successful grain reaper at 22; Sholes was 48 before he contributed his part of the typewriter; and Sir Hiram Maxim produced his machine gun when he was almost 50. I have no doubt Edison was not to be treated lightly as an inventor in his ripe old age—patents continued to issue in his name after his death at 84. Even teen-agers have come up with things I thought involved invention. I conclude that inventions and discoveries come to young and old—so don't worry too much about your age if you are receptive to invention.

Perhaps I had better explain "receptive to invention." To me it means being everlastingly mentally alert and mentally curious about the unexplainable, the unexpected, the unpredictable —yes, the accidents, for therein often lie the great discoveries and inventions. Goodyear tried long and hard to vulcanize rubber without success. Then came the accident. Rubber and sulphur fell on a hot stove; the accident produced vulcanized rubber. Goodyear was alert, recognized what happened, and made a "discovery" ("discovery" and "invention" are treated synonymously in our patent law).

One of Edison's greats, the phonograph, came from his insatiable search for an explanation. He was working on his telegraph repeater that included a motor-driven cylinder. The motor had gone berserk and a contact on the cylinder produced strange and most undesirable sounds. While his immediate purpose was to fix the machine, he was unable to put aside the thought that the combination might have other uses. Perhaps he could modify the surface of the cylinder to produce a desired sound? He experimented with surface materials; found tinfoil suitable; and on August 22, 1877 requested John Kruesi to make a manually rotatable cylinder and a stylus arrangement. Edison applied tinfoil to the cylinder; shouted through the mouthpiece, thus actuating the stylus, and to everyone's surprise the machine talked back. Thus, the phonograph was born when Thomas Edison was 30 years old. Incidentally, patentwise he landed in a virgin field. Do I hear shouts of anguish from beyond the Iron Curtain?

Most inventions selected for this review did not arise by accident or in a virgin field. I do not recommend that you just sit waiting for accidents to happen—but do not overlook the latent possibilities of the unexpected. Perhaps we have arrived at the educational stage when deliberate, thoughtful approach to invention is most apt to pay off. I have in mind Wilbur and Orville Wright. When they made their first successful flight and landing at Kitty Hawk, around the beginning of our century, it was not on a virgin field of invention.

The Wrights had been aware of the many successful glider flights of Otto Lilienthal. They knew that he shifted his weight to balance his glider. They were satisfied that the shifting weight idea provided insufficient control and

was probably the cause of the gliding accident resulting in Lilienthal's death. Wrights found existing scientific data on airfoils unreliable. The two brothers devised and operated a small wind tunnel. Their wind tunnel experiments determined the lift and drag of many differently shaped airfoils operated at different angles. They developed a system of wing warping and of varying air pressures to provide the necessary equilibrium.

In October 1902 they designed a heavier-than-air flying machine. The machine was powered by a 12-horsepower, 4-cylinder gasoline motor. The airplane, including pilot, weighed 750 pounds. Orville successfully flew the machine at Kitty Hawk, N. C., on December 17, 1903. The flight lasted 59 seconds at a speed of 30 miles per hour. By October 5, 1905, Wilbur flew for 38 minutes over a small circular course covering 24 miles. Thus we have one example of a painstaking investigation that resulted in a successful invention where Leonardo, Lilienthal and many others tried with doubtful success or failed entirely.

There is another approach to invention that Edison used on occasion. We might call it a "brute force" approach. The majority of electrical engineers thought that electric lights must be operated by sending current through the illuminating devices in series. This required low resistance filaments that dissipated a heavy current. Edison courageously decided that the majority were in error. He started a search for a suitable filament. The filament had to be of small diameter, high resistance, and of long life. Some carbonized threads showed promise. He sent men all over the world looking for fibres that might have the necessary characteristics when carbonized. By sheer numbers of experiments and effort he succeeded about 1879. It now looks like a brute force approach and, perhaps there was no other. Also do not forget that he went contrary to the pack.

On occasion the invention *seems* to come so easily—once the need is clearly recognized *and the solution vigorously sought.* McCormick's Grain Reaper is an example. Cyrus Hall McCormick was the son of a farmer who had invented numerous devices for farm use. The father made repeated, but unsuccessful efforts, to build a grain-cutting device. In 1831, at the age of 22, young Cyrus took up the problem. He developed the reaper which was used successfully in the harvest of 1831 and was patented in 1834.

When Eli Whitney graduated from Yale in 1792, he had already demonstrated mechanical ability. Mrs. Nathaniel Greene, widow of the Revolutionary War General, invited Whitney to Savannah. While there and considering his future course, he made several ingenious household contrivances. He was introduced to some gentlemen who were discussing the need for a machine to separate cotton from its seeds. Within a few weeks Whitney produced a model. It consisted of a wooden cylinder carrying rows of spokes that extended through a comb set to pull the lint but not passing the seed. The model was operated by hand and was capable of separating 50 pounds of cotton lint per day. Thus the reaper and the cotton gin inventions appear to have been born painlessly.

Sometimes the mental act of inventing unfolds itself quite quickly and completely. Nevertheless, the actual operable device is developed very slowly. Lack of funds, facilities, or many other difficulties seem to intervene. According to Supreme Court records Samuel Morse, by profession a historical painter, was returning from Europe in 1832 on the packet ship *Sully.* The brilliant conversations of his fellow shipmates as to electrical matters helped him to see that by means of electricity, signs representing figures, letters, or words, might be reproduced at any distance.

Before he landed in the United States, he had conceived and drawn out in his

sketch book, the form of an instrument for an electromagnetic telegraph. Morse had arranged and noted down a system of signs composed of a combination of dots and spaces, which were to represent figures. These were to indicate words to be found in a telegraphic dictionary, where each word was to have its number.

Unable to purchase the materials for a battery and wire, Morse was compelled, for subsistence, to return to his art. From 1832 to the latter part of 1835, there was no opportunity to test the invention. He never lost faith in its practicability, nor abandoned his intention of testing it as soon as he could command the means.

In 1835 Morse was appointed Professor in the University of the City of New York, and occupied rooms in the University buildings. Here he immediately commenced his telegraph experiments.

The completed instrument was exhibited in February 1838 in The Franklin Institute at Philadelphia, where it operated through a circuit of ten miles of wire. The telegraph was taken to Washington where it was publicly exhibited in the House of Representatives. A Committee of the Congress examined it, made a favorable report, and recommended an appropriation of thirty thousand dollars to test the utility of the invention.

Most readers probably know that Morse constructed a telegraph line from Washington to Baltimore and successfully demonstrated its operation. Do not overlook the years of effort and the inventor's implicit faith in his invention. I am sure that without great faith many inventions would have died a-borning. So, have great faith.

You can be reasonably sure that your mind will be involved when you make an invention because it is the mind which creates or conceives or devises. We do not need to get too psychological about it, but it will help if you realize that the process may be deliberate and conscious, or unexpected and subconscious. Although inventors rarely tell us about the mental process through which their inventions were coined, I suspect that not infrequently inventions arrive through a subconscious process.

The inventor may start by recognizing a clear need but, try as he will, he does not succeed in conjuring up the instrumentality. The harder he seeks the solution, the more it eludes him. The wise inventor may put the problem aside. He may even sleep on it for that often seems to help. But, whatever the process, he thinks of something else and the first thing he knows the answer arrives by some little understood subconscious mechanism.

I recall Hiram Percy Maxim, son of Sir Hiram and nephew of Hudson Maxim, telling about his invention of the gun silencer. He liked to shoot at a target with a small rifle but he did not like to annoy his neighbors. If he could only put something on the rifle to eliminate the noise, target shooting would be so much more enjoyable. He did not have the vaguest idea of how to accomplish the desired result.

One morning after shaving, Maxim released the water from the lavatory. The water did not suddenly disappear but after a rotary action, went slowly down the drain. He quickly realized that if the gases from the exploding cartridge in the rifle could be made to expand slowly by a rotary motion, instead of suddenly being released from the muzzle, the noise would be reduced. It did not take long to make a cylindrical device with a straight hole for the rifle bullet and a tortuous expansion space for rotating the gas and trapping the sound. Thus the gases came out slowly and the noise was silenced. Maxim may have arrived at the result by the subconscious process. Some reasoning by analogy was also involved.

Seeking advice sometimes encourages an inventor. If you decide on that course, go to the truly great for they

can afford to render sound, honest judgment. Alexander Graham Bell might not have gone down in history as the inventor of the telephone had he not consulted the famous Professor Joseph Henry.

Bell, conceiving the speaking telephone in the year 1874, had serious doubts that the device would be practical because of the feebleness of the voice-generated electric currents. After explaining his views to Professor Henry in 1875, Bell wrote to his father and mother as follows:

> I felt so much encouraged by his interest, that I determined to ask his advice about the apparatus I have designed for the transmission of the human voice by telegraph. I explained the idea, and said, "What would you advise me to do; publish it and let others work it out, or attempt to solve the problem myself?" He said he thought it was the germ of a great invention, and advised me to work at it myself, instead of publishing. I said that I recognized the fact that there were mechanical difficulties in the way that rendered the plan impracticable at the present time. I added that I felt I had not the electrical knowledge necessary to overcome the difficulties. His laconic answer was, "GET IT."
>
> I cannot tell you how much those two words have encouraged me. I live too much in an atmosphere of discouragement for scientific pursuits. Good (Mr.) ———— is unfortunately one of the *cui bono* people, and is too much in the habit of looking at the dark side of things. Such a chimerical idea as telegraphing *vocal sounds* would indeed, to *most minds*, seem scarcely feasible enough to spend the time in working over. I believe, however, that it is feasible, and that I have got the clue to the solution of the problem."

Note also the "accidental" approach in Bell's work on the telephone. His attorney arguing before the U. S. Supreme Court said this about Bell:

> In performing . . . an experiment with a . . . telegraph which employed two reeds or springs vibrated in front of an electromagnet, one of the springs was accidentally knocked, and thus set in vibration. He found that this slight vibration produced a sound from the spring of another instrument connected in electrical circuit. With another man the trivial accident might have passed unnoticed. But he instantly joined it with his older thoughts. The marriage was fruitful and the speaking telephone was born. It thenceforth needed only nurture. It at once struck him that if he was right in his observation of this accident, then the feeble vibrations of a spring in front of an electro-magnet had developed sufficient electric currents to produce audible sonorous effects at a distance. He repeated the experiment . . . , sanguinely satisfied that his former fears about the feebleness of the currents were ill founded, he instantly gave orders for the construction of a speaking telephone with a membrane diaphragm. . . .

I do not wish to overlook the courage frequently found in inventors. Bell was an example. The first instruments, ill-made, broke on the first trial. They were repaired without much success. It is not certain that a single spoken word was understood during the early experiments. Bell was in great trouble financially. He pawned his watch, borrowed from friends, and was heart-broken for other reasons. Nevertheless, he kept on. At one period Mr. Bell was so much in need that a friend of the family advanced $25 per month for six months. So lack not in courage.

Among the previously mentioned paths to invention were accidental, brute force, the apparently easy, deliberate and conscious, unexpected and subconscious, and the requirement of receptivity. Before I completely forget, we had better

get to persistence, which many of our outstanding inventors exhibited in force. Bell, Edison, Morse, and the Wright Brothers were certainly persistent, and you know where it got them.

John Philip Holland's invention of the submarine wins my nomination for unabated persistence. The Civil War engagement of the *Merrimac* and the *Monitor* suggested the submarine to Holland. His first underwater boat was built in 1875. It failed, as did Holland's second, third, fourth, fifth, sixth, seventh, and eighth boats. His ninth submarine, finished in 1898 after 23 years of untiring efforts, turned out to be serviceable! So, be persistent.

The reader may wonder if invention demands a particular education. I doubt that a study of the 19th and early 20th century inventors' education will be very helpful in forecasting the requirements of the last half of the 20th century. We know that Thomas Edison, Hudson Maxim, James Watt, Sir Hiram Maxim, Elias Howe, and the Wright Brothers, just to mention a few outstanding inventors, lacked a "formal" education. Guglielmo Marconi and Alfred Nobel, the inventor of dynamite, were privately educated. On the other hand Eli Whitney, Lee de Forest, Samuel Morse, Hiram Percy Maxim, and others equally notable were college graduates. It was probably a matter of intelligence rather than where or how the education was obtained.

From what I've read of Henry Ford, I'd conclude that he thought formal education might be dangerous to originality and of that we know he possessed plenty. However, I'd really be surprised if his grandson Henry Ford II decided that men with a college degree were incapable of refreshing originality. I believe we are entering an age when true scientific knowledge will be a tremendous factor in invention and discovery. But I do not believe that you are ruled out if you got your knowledge "the hard way"—provided you got it! Remember Professor Henry's advice to Bell: "GET IT!"

I can just hear some impatient reader snort: "Enough of this psychological and philosophical verbiage! Tell us what to invent, or how to invent." Well it may be that I have used different words, but I have tried to point out some of the ambient circumstances that may help you to be receptive to invention, and that is as near as I propose to come to any specific discourse on "how to invent."

At least one book has been written with many suggestions of "what to invent" and I suppose a diligent search would disclose other "please invent" lists. Before you undertake casually to fill these expressed needs, I urge you to study the literature, the patents, the previous approaches, and the waiting market. Usually you'll find that others have proposed solutions—some practical and some impractical. You may ask "Why have not the practical solutions been adopted and marketed?" Some may have been too early—before their time. The inventors may have found the commercial path too trying, or too difficult, or too long.

Eli Whitney tried to market the cotton gin but he had infringers galore. Whitney became involved in patent litigation. Although his patent was finally sustained, Whitney had given up in disgust and started to manufacture firearms for the United States Government. Even at that Whitney could not shut off his capacity for originality for he is credited with introducing factory division of labor and standardization of parts.

What to invent? Fortunately, the area of invention is as boundless as the universe. I do not suppose that there is an industry, an art, a science, a business, or any sphere of human endeavor that is not at this very moment crying for originality, for new things, for new methods. A catalogue of even a few of the inventions and discoveries as yet

unborn would fill many pages of fine print.

General David Sarnoff, at a luncheon in honor of his forty-five years in radio, asked for three inventions as presents for his fiftieth anniversary. You may be interested because as a bystander you might have thought that each of the inventions was already in use. In a manner of speaking they are, but what General Sarnoff requested will demand no small measure of perseverance and a great measure of originality.

I doubt if he is much concerned with the order of their appearance. So here goes: First, a practical and truly novel method of recording the video portion of television programs so that they can be reproduced with fidelity and at low cost anywhere at any time. Second, a true amplifier of light that will make possible inexpensive projection of television pictures in the home. There must be adequate light, rapidity of control, and distortionless enlargement. Third, an electronic air-conditioner that will provide for the home natural air conditioning with a minimum of noise and preferably without any mechanically moving parts. I may have included a few limitations that General Sarnoff tacitly implied. Incidentally, he only allowed five years, so you had better get busy! In the meantime industry waits.

I do not have any anniversary coming up, I have earned no right to request presents, and besides my wants are so very simple. I'll just go to the nearest drug store and try to buy the unattainable—a practical, neat, sanitary, refillable, tooth paste dispenser with a cap that refuses to get lost. And please note that "refillable" is *not* synonymous with "collapsible" in my dictionary. By way of encouragement for the inventor —I shall not insist on an unhappy degree of cheapness! Will one of my readers just come up with that necessary and long awaited invention? So, you still want to be an inventor?

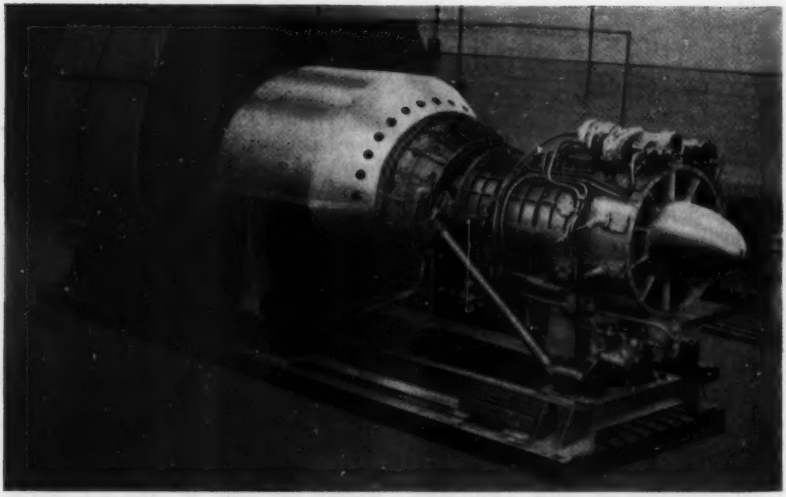


FIG. 1—G2-Type Naval Gas Turbine.

THE G-2 TYPE NAVAL GAS TURBINE

ACKNOWLEDGMENT

This article was published in the February 1953 edition of "The Shipbuilder and Marine Engine-Builder."

On the 14th July, 1947, the triple-screw experimental naval craft *M.G.B. 2009*, the first ship in the world to be propelled by a gas turbine, put to sea. The gas turbine, known as the Gatric, and rated at 2500 shp, was designed and manufactured by the Metropolitan-Vickers Electrical Co., Ltd., of Trafford Park, Manchester. The engine was of the open-cycle type, without heat exchanger, and consisted of a gas generator, based upon the F2 jet engine, and a separate power turbine.

Following the successful operation of the Gatric at sea, an order was placed with the same firm for four larger gas turbines employing the same cycle as the Gatric engine, and these became known as the G2-type.

The G2 gas generator (compressor, combustion chamber, compressor turbine and auxiliaries) is, with certain modifications, similar to the Beryl jet engine. It was originally designed to develop 4800 shp, but, after operational experience at sea, the maximum power

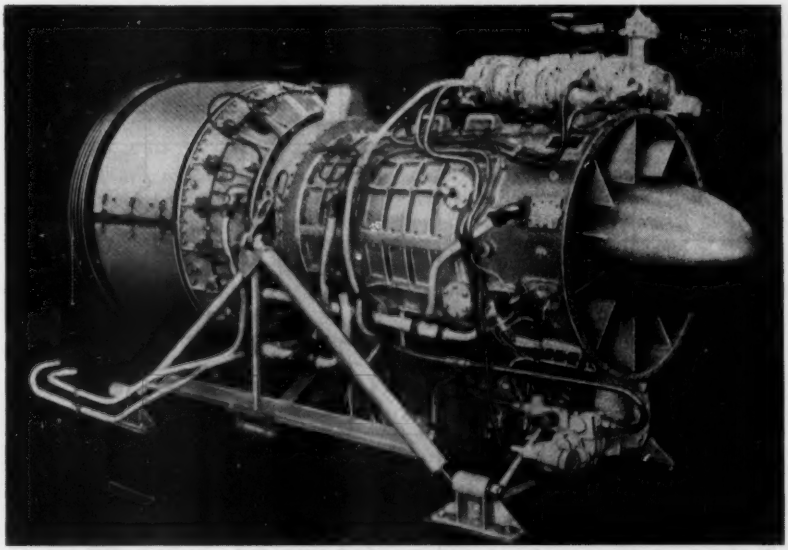


FIG. 2—Gas Generator.

has been declared at 4500 hp, with a maximum continuous rating of 4000 shp.

Following the practice employed in the *M.G.B. 2009*, the gas turbines are used only at high speeds, and are designed for a total life of 1000 hours, of which 300 hours may be run at maximum power. Diesel engines provide the necessary power for cruising and maneuvering

A complete G2 unit consists of a gas generator, a power turbine with exhaust duct, and a reduction gear. The power turbine, which is mechanically independent of the gas generator, drives the propeller shaft through a single-helical side-pinion reduction gear. A photograph of the complete unit is reproduced in Fig. 1.

It will be appreciated from the figures given in the accompanying table that the 4500-shp gas turbines have a much better power-weight ratio than the 2500-shp Gatric unit.

DETAILS OF POWER/WEIGHT RATIOS

	Gatric	G2
Rating, S.H.P.	2500	4500
Weight of gas-turbine unit (excluding gears), lb	4350	6949
Weight of gears, lb	2600	2772
Total weight, lb	6950	9721
Power/weight ratio, gas turbine only, lb/S.H.P.	1.74	1.54
Power/weight ratio, complete unit, lb/S.H.P.	2.78	2.16

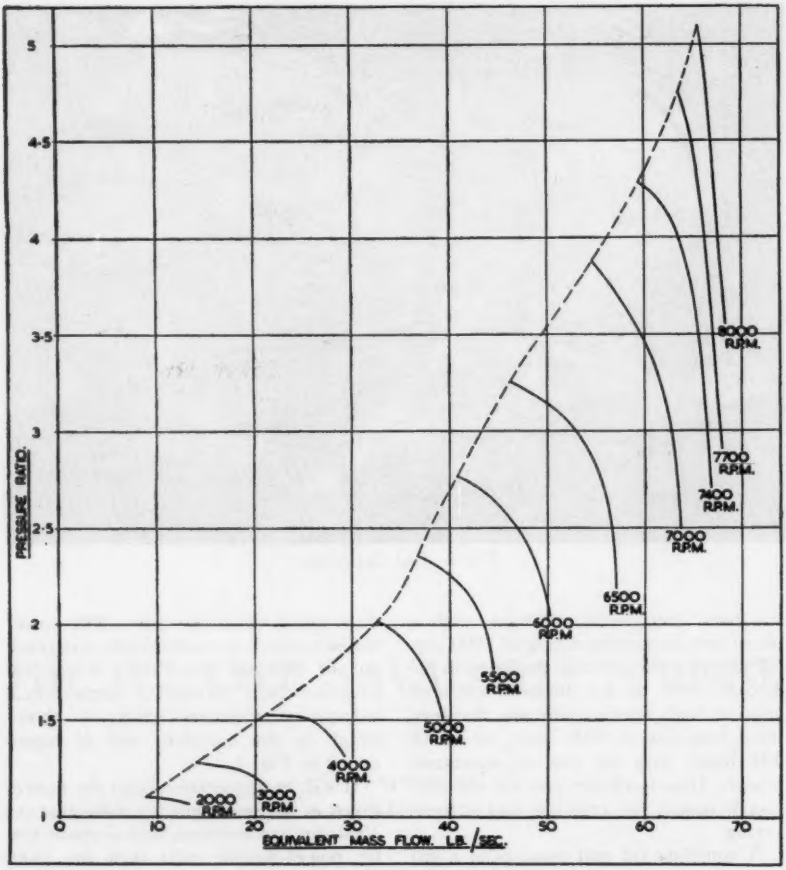


FIGURE 3. —General Characteristics of Compressor.

Gas Generator.—

The gas generator, illustrated in Fig. 2, is supported by a built-up frame, located at each side of the compressor and bolted to the engine bearers. The frames are pivoted so that they can swing outwards to allow for radial expansion. The forward end of the compressor is supported under the inlet branch by a small pivoted frame, which permits axial expansion. Alignment of the unit is maintained by a sliding key, which is located under the compressor outlet branch.

With 11 axial-flow stages, the compressor produces an overall pressure ratio of 4.03 at an air-mass flow of 62.6 lb per second for a maximum speed of 7830 rpm. The rotor consists of an inlet-end piece of manganese-molybdenum steel, a drum front extension, a drum center portion and drum conical

extension pieces of aluminum alloy, and a turbine end shaft of nickel-chrome-molybdenum steel. The compressor casing is of aluminum alloy. Two bearings (one ball and one roller), having mist lubrication, are provided for the rotor. The moving blades are of aluminum alloy, and are carried in longitudinal serrated grooves in the rotor; while the fixed blades, which are also of aluminum alloy, are accommodated in dovetailed grooves in the casing. Provision is made for the removal of salt deposits from the compressor blading.

The general characteristics of the compressor are shown in Fig. 3.

The annular combustion chamber is of Firth-Vickers Immaculate 5 stainless steel, with fixing rings of Firth-Vickers FCB(T) austenitic steel, and is designed to give straight-through axial flow. Fuel, in a finely atomized state, is injected through 20 fixed orifices into the primary chamber. The single-stage gas-generator turbine has a molybdenum-vanadium-steel disc, mounted on a steel shaft attached to the compressor-drum conical extension-piece. The moving blades, which are secured to the disc by fir-tree fastenings, are made of Nimonic 80A alloy, which has also been used for the fixed diaphragm blades. Air is tapped from the compressor for cooling the turbine disc. The maximum gas temperature at the inlet to the nozzle guide vanes of the gas-generator turbine is 806 deg. C.

Power Turbine.—

The forward end of the power turbine is carried by two semi-flexible legs, attached to brackets on the outlet branch and mounted on a cross-beam bolted to the engine bearers. The after end of the turbine is supported from the gear-box. In order to maintain alignment, a sliding key is provided on the turbine bottom center-line.

The rotor, which consists of three Firth-Vickers FCB(T) austenitic-steel forgings welded together, is carried by one ball bearing and one roller bearing, each of which is lubricated by means of an oil mist. The moving blades are also of Firth-Vickers FCB(T) austenitic steel, while molybdenum-vanadium steel has been chosen for the fixed diaphragm blades. The FCB(T) austenitic-steel turbine casing and the mild-steel exhaust casing, which have greatly different coefficients of expansion, are joined by an expansion piece, the material of which has an intermediate coefficient of expansion.

The power turbine is designed to operate at a maximum speed of 5200 rpm, and the mean gas-turbine temperature at the power-turbine inlet, measured by four thermocouples, is 660 deg. C. Due to stratification of temperature across the annulus, this figure is some 20 deg. C. higher than the average temperature calculated from the fuel flow.

From the forward flange of the combustion chamber to the after end of the exhaust casing, the engine is lagged and enclosed in a sheet-aluminum casing, built in easily removable sections. The ejector effect of the turbine exhaust is to draw air into the aluminum casing, and the cooling effect of this air-stream is such that, at full power, the casing can be touched by hand, comfortably. The casing also serves to remove vapor and fumes from the engine-room. All controls, valves, burners, electrical equipment, etc., are located outside the casing and are readily accessible.

Gears.—

Power from the turbine is transmitted to the propeller through a side-pinion single reduction gear, encased in a light-weight rigid casing of all-welded steel construction. The overall gear ratio is 4.73 and the maximum propeller-shaft speed is 1100 rpm.

The gear wheel and pinions are machined from nickel-chrome alloy-steel forgings, and the single-helical gear teeth are hardened and ground. Roller-type bearings are provided for both the pinion and wheel shafts, and a Michell

thrust block is incorporated in the after end of the gear case. Solid flange couplings join the pinion and power-turbine shafts and the slow-speed wheel shaft to the propeller shaft.

Fuel-control System.—

The engines are designed to operate on Pool gas-oil, and the power output is controlled solely by regulating the fuel quantity to the combustion chamber of the gas generator. The speed of the gas generator determines the temperature, pressure, and flow rate of the gas at the inlet to the power turbine. The high-pressure fuel pump, which is driven from the gas-generator rotor, delivers 630 gallons of oil per hour at a pressure of 600 lb per sq. in. (gage), and at a maximum pump speed of 3620 rpm.

For speeds greater than 3000 rpm, the fuel supply to the burners is regulated by the main control valve. This valve consists, essentially, of a servo-operated calibrated needle which moves in an orifice. Movement of the needle is such that a sufficient quantity of oil is passed through the orifice to the burners, by way of the trip valve, overspeed governor valve and isolating valve, to give a rate of acceleration as high as possible, without stalling the compressor.

As a prevention against overspeeding, the gas generator is provided with a ported-sleeve centrifugal governor, which reduces, by throttling, the fuel quantity passed to the burners. The speed of the power turbine, which is mechanically independent of the gas generator, is controlled, under normal conditions, by the relationship between the power input from the gas generator and the power absorbed by the propeller. However, if the speed rises to a predetermined value above the normal operating speed, one of two emergency trip governors of the bolt type (one located on the turbine shaft and one on the gearbox-pinion shaft) will automatically close the fuel trip valve, stop the supply of fuel to the gas generator, and, consequently, the flow of gas to the power turbine. The tripping mechanism is reset by an electrically-controlled air piston.

The maximum output of the engine is limited by the maximum permissible gas temperature at the inlet to the power turbine.

Lubricating-oil System.

When starting-up, an electrically-driven auxiliary pump circulates the oil, in a closed circuit, from the gearbox sump to the gear teeth and thrust block. When the propeller shaft attains a speed of about 350 rpm, the main pump, which is driven from the turbine shaft, comes into operation and supplies oil to the gearbox. With the main pump in operation, the auxiliary pump can be switched off. A scavenge pump returns the oil from the gearbox sump, through a cooler, to the storage tank.

Oil is supplied to the gas-generator and power-turbine bearings (ball and roller) by the gas-generator oil pump, which is driven through reduction gearing from the gas-generator shaft. These ball and roller bearings are lubricated by an oil mist, formed by spraying into the bearing a small quantity of oil, with compressed air tapped off from the compressor. With this arrangement, the oil is not recovered. Mist lubrication is also provided for the overspeed governor.

An auxiliary pump, driven from the turbine shaft, supplies oil to the power-turbine bearings during the long periods of cruising, when the gas plant is out of service and the trailing of the propeller causes the power-turbine shaft to rotate. The compressor rotor of the gas generator is rotated slowly by an electric inching motor.

Air System.—

A light-weight compressed-air motor, supplied with air at a pressure of 450 lb per sq. in. (gage), from storage batteries, is used for starting the gas generator. When a speed of approximately

2000 rpm is attained, the unit becomes self-sustaining and the motor is no longer required. After ignition, it is possible to accelerate the gas generator from standstill to 2000 rpm in about 30 seconds. To increase the speed of the gas generator from the self-sustaining speed to the idling speed (3000 rpm), fuel is passed by the boost and high-pressure fuel pumps, through a fixed orifice, by-passing the main fuel-control valve. A further supply of high-pressure air, reduced in pressure to 100 lb per sq. in. (gage), is used to operate the power-turbine trip and reset mechanism.

Air is tapped from the gas-generator compressor at various stages for oil-mist lubrication and cooling of the gas-generator and power-turbine bearings, for cooling the gas-generator turbine disc, to force the distilled water from the storage tank to the compressor spray ring, as a servo-medium for operating the gearbox overspeed trip mechanism, and to balance the compressor thrust.

Electrical System.—

The electrical system is divided into three sections, *viz.*, 24-volt d.c. circuits, 220-volt d.c. circuits, and the various instrument circuits.

Three solenoid valves and two ignition boost coils operate on 24-volt circuits. One solenoid valve controls the supply of fuel to the igniters, one controls the supply of high-pressure air to the starting motor, and the third controls the air supply to the power-turbine emergency-governor reset piston. The two ignition boost coils supply the high-tension current to the spark plugs used to ignite the two-torch igniters.

The inching motor and the auxiliary lubricating-oil pumps are connected to the main 220-volt d.c. circuits.

In both the 24-volt and 220-volt d.c. circuits, suppressors are provided to prevent interference by the boost coils and the inching motor. Limit switches, mechanically connected to the fuel-control and isolating valves, are interlocked electrically with the solenoid valve for the starting motor, and with the inching motor and its contactor. This arrangement ensures that the starter-motor solenoid valve cannot be energized if the fuel-control valve is open, and also that the inching motor cannot be started when either the starting-motor solenoid is energized or the fuel-isolating valve is open.

Tests.—

Extensive bench tests were carried out on the G2 engines, and the curves reproduced in Figs. 4, 5 and 6 give the data obtained regarding specific fuel consumption/propeller-shaft speed, propeller-shaft output/propeller-shaft speed,

FIGURE 4.

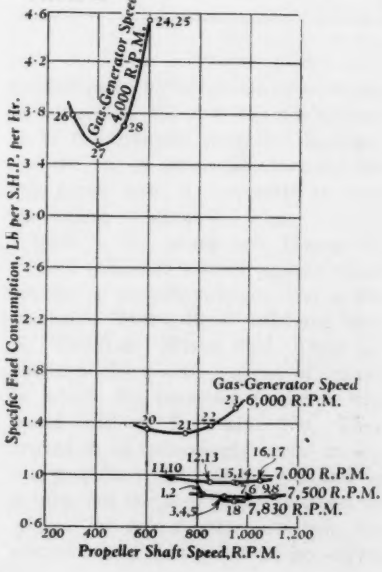


FIGURE 5.

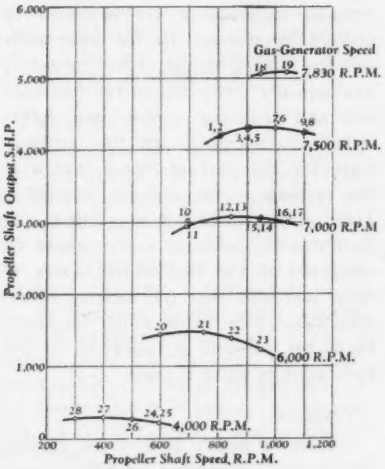
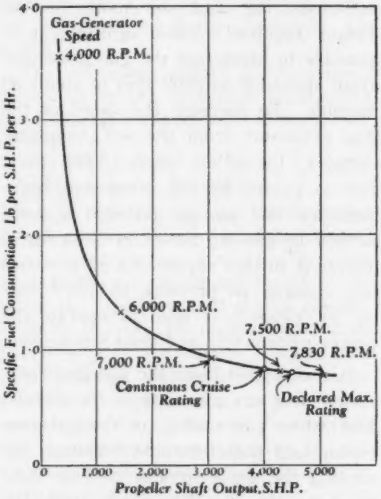


FIGURE 6.



and specific fuel consumption/propeller-shaft output, at various gas generator speeds. These performance figures are considerably better than those of the 2500-shp gas turbine; they show a greater output with a much less specific fuel consumption. The G2 gas turbines are at present undergoing sea trials.

A RELATIONSHIP FOR PRELIMINARY PROPELLER DIAMETER

EVERS BURTNER

THE AUTHOR

Was educated in public schools of Williamsport, Penna., and Lynn, Mass. He graduated from Massachusetts Institute of Technology, SB, Class of 1915. He was then employed as a Draftsman at the Portsmouth Naval Shipyard, until becoming Port Engineer for John S. Emery & Co., operators of U. S. Shipping Board tonnage, 1919-1920.

Since 1920, the author has been Instructor, later Assistant and Associate Professor of Naval Architecture and Marine Engineering at Massachusetts Institute of Technology. He has also been with the Central Technical Department, Bethlehem Steel Co., Quincy, part-time or summer, from 1932 to 1946.

In the past, many papers have appeared in the AMERICAN SOCIETY OF NAVAL ENGINEERS' JOURNAL dealing with various methods of sizing propellers, checking their performance and chance of cavitation.

Early in the design stage, it is very desirable to know fairly closely the diameter of the propeller to provide enough propeller clearance and submergence. The hull lines in the vicinity of the propeller should be drawn by the naval architect having in mind the proportions of the propeller of optimum efficiency and desirable clearance from the hull form and such appendages as rudder, struts or bossing. Furthermore, the marine engineer in his preliminary work will find it useful to study the feasible propeller revolutions per minute at full power. Even if it is not feasible to fit the optimum propeller diameter, i.e., the one of maximum efficiency for any given rpm, it frequently is very convenient to know this size.

Quite a few years ago, George F. Crouch published several very excellent articles on propeller design, first in the magazine "Motor Boat" 1919 and later in "Yachting," March 1932. These included a chart with a series of curves in which the propeller diameter was based only on Rpm and Shp. They proved to be exceedingly useful in sizing propellers for motor boats and in getting out the preliminary diameter of wheels for larger ships. In fact, my attention was first called to his charts

while working with the technical division of a prominent Atlantic Coast shipyard.

Mr. Crouch has indicated that in their final form they represent a compromise between the D. W. Taylor Propeller Charts and actual data based on adjustments made after use. Recognition of the popularity of this type of chart is shown by the fact that they were reproduced or similar charts were published in Germany, Sweden, Great Britain, and Japan.

The general form of Mr. Crouch's curves led the author to feel that a compact formula could be developed to approximate them.

For many years the Taylor and Troost open water propeller charts have been very useful. Some of the most popular are based on shaft horsepower per screw, rpm, and V_a, ship speed thru the wake water at the screw, knots.

For given shp, rpm and V_a values, the value of the power parameter $B_p = \frac{shp^{0.5}(rpm)}{V_a^{2.5}}$ can be computed. Reference to the above open water propeller curves and entering with this B_p value will indicate a maximum open water propeller efficiency and the corresponding particular δ value. The latter will provide the diameter, D as $D = \frac{\delta V_a}{rpm}$. Propeller efficiency is higher for lower B_p values, i.e., say in the range of 5 to 10.

When the parameters

$$B_p = \frac{shp^{0.5}(rpm)}{V_a^{2.5}}\ ;\ \delta = \frac{D\,(rpm)}{V_a}$$

are solved for V_a and equated, the following equation results:

$$\text{Diameter } D = \frac{\delta}{B_p^{0.6}} \frac{shp^{0.2}}{rpm^{0.6}}$$

If the ratio $\frac{\delta}{B_p^{0.6}}$ is nearly constant for B_p values of 5-10 which correspond to high propeller efficiencies, we will have shown that a compact formula for propeller diameter is possible.

Through the use of the Troost curves for four blade propellers of expanded area ratio of .40 the following values of $\frac{\delta}{B_p^{0.6}}$ were computed:

B_p,	5	10
δ, corresponding to maximum efficiency	93.5	129
$\frac{\delta}{B_p^{.6}}$	49.1	51.3

Thus the fact that values of $\frac{\delta}{B_p^{0.6}}$ run nearly the same for B_p values of 5 and 10 allows us to conclude that a formula for optimum propeller diameter can be given as:

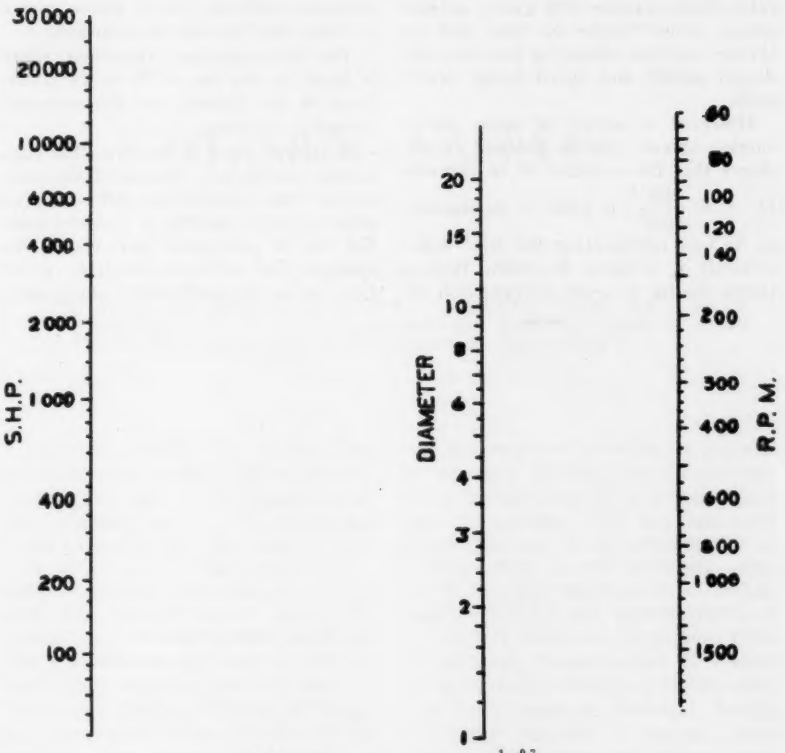
$$D = 50 \frac{shp^{0.2}}{rpm^{0.6}}$$

It will be noted that curves of four bladed propellers were used to derive the coefficient 50. Four blade wheels have been universal until lately for single screw ships; also the small difference given by the use of three blade or five blade charts in developing the coefficient can be neglected in a formula for preliminary design.

Mr. Douglas MacMillan includes the above equation in his section on Marine Engineering in the current edition of Kents Handbook, Power Volume, edited by Kenneth Salisbury. MacMillan and others find that this optimum propeller diameter formula is very useful in preliminary design.

This equation in the form here given was derived prior to 1930 to illustrate to an engineering design class the development of a convenient formula for propeller diameter of optimum efficiency, the relationship of the basic variables and the construction of an alignment chart representing the same.

In the discussion of Sir Amos Ayre's recent paper on a propeller formula, Mr. W. Benson recalled that his associate, Peter Doig, in a brochure on propeller design included a formula $D = 48.5\ Shp^{0.2}/RPM^{0.6}$. However, it does not appear in his article on Pro-



Alignment Chart $D = 50 \frac{shp^{0.2}}{rpm^{0.6}}$

peller Design in International Marine Engineering in 1913.

At this period Taylor and Froude's methodical series of open water propeller experimental data and curves were becoming available. They proved popular among designers; hence, Doig's formula was overlooked by the writer and undoubtedly others.

It is true that the selection of propeller diameter or pitch greater than the calculated value with some prime movers will adversely limit propeller revolutions. This in turn, due to propeller Shp-rpm characteristics, will mean lower Shp and ship speed than desired. For instance, with a direct drive diesel engine the engine mean effective pressure, (MEP), could be increased; but that procedure is normally considered undesirable to correct excess propeller torque on trials. With the ship in service and the bottom becoming foul, ship resistance will naturally increase anyhow; the accompanying extra power for the same speed would require more torque and hence more MEP.

Dr. Troost has stated that, with diesel direct drive, it is quite common in Europe to take a propeller diameter slightly smaller than the size which our open water propeller test charts will indi-

cate. Such practice will guard against excess wheel torque on trial and in service, and the chance of less than the design power and speed being developed.

However a survey of some recent single screw standardization trials shows that the constant 50 in formula $D = 50 \frac{shp^{0.2}}{rpm^{0.6}}$ is fully as satisfactory as 48.5 in representing the trial data; certainly it is easier to recall. It is a simple matter to apply a correction on diameter with the type of prime mover in mind after the size is computed.

The accompanying alignment chart is based on the use of 50 as the coefficient in the formula for the optimum propeller diameter.

It is only right to reaffirm that particular conditions, limited draft, etc., will in some installations call for a propeller which is smaller in diameter than the one of maximum open water efficiency. The optimum diameter given here is for the preliminary study only.

TITANIUM—A SURVEY

ACKNOWLEDGMENT

This article was presented to the Royal Aeronautical Society in London on 29 January 1953 by P. L. TEED. It was published in abridged form, in the 20 February, 13 March and 27 March 1953 editions of "Engineering."

Titanium, unlike the metals first known to man, is not found in the elemental state, but, in combination with other elements, it is widely distributed in the earth's crust. The titanium minerals which are of commercial importance are ilmenite, a combination of iron oxide and titanium oxide, and rutile, consisting of titanium oxide. Both are widely distributed. Ilmenite is found in beach sand deposits, such as those of Travancore (India), Florida and Senegal. Travancore is currently by far the most important producer of this type, its total output since 1924 having been more than 4 million tons. At the present time the principal sources of the mineral are the great ore-bodies at Sogndal in Southern Norway, in the Adirondacks in New York State, and at Allard Lake in Quebec. This last and most recent discovery is so large that it is probable that it will ultimately make North America independent of Indian supply. A third and smaller source of the mineral arises as a by-product from the magnetic concentration of certain tin ores, such as those of Malaya and, to a lesser extent, of Portugal. Rutile, in smaller demand, is derived, often with other products, from beach sands in Australia (Queensland and New South Wales). It is also available in pebble form in the French Cameroons.

PRODUCTION OF METALLIC TITANIUM

The Kroll process has virtually produced the whole of the titanium so far used for engineering purposes. Simple in conception, it involves chemical engineering problems of the utmost difficulty and complexity. It consists of reducing titanium tetrachloride by a chemically more active metal, magnesium.

The chemistry of Kroll's process is shown in the following equation:

$$TiCl_4 + 2Mg = Ti + 2MgCl_2 \quad . \quad (1)$$

Put in another way, to produce a pound of titanium, theoretically, requires a pound of magnesium. In practice, about one and a quarter pounds are employed. This indicates to the engineer that titanium, made by this process, cannot be cheap.

The chemistry involved in production of titanium tetrachloride is expressed by the following equation:

$$TiO_2 + 2C + 2Cl_2 = TiCl_4 + 2CO$$

Titanium tetrachloride, at normal temperature and pressure, is a liquid having the following physical characteristics: density at 15 deg. C., 1.76; melting point, −25 deg. C.; boiling point (at normal pressure), 136 deg. C. It is decomposed by water and by aqueous vapor, which accounts for its use as a material for the production of smoke screens. Magnesium has a density at 15 deg. C. of 1.74; a melting point of 651 deg. C.; and a boiling point (at normal pressure), of 1120 deg. C. Titanium has the following characteristics: a density at 15 deg. C. of 4.5; melting point of 1725 deg. C.; its boiling point has not been determined.

Anhydrous magnesium chloride is extremely hygroscopic. It forms, with water, hydrated salts which decompose, on heating, into magnesia and hydrochloric acid. In its anhydrous form it has the following features: density at 15 deg. C., 2.32; melting point, 708 deg. C.; boiling point, 1412 deg. C. These differences in physical characteristics indicate some of the difficulties in bringing about the reaction indicated in equation (1). It is, however, the respective chemical properties of the different substances, and the extreme sensitivity of titanium to traces of oxygen and nitrogen, which makes this problem of formidable dimensions. Both titanium tetrachloride and anhydrous magnesium chloride react with aqueous vapor. Metallic magnesium, if molten, must be out of all contact with oxygen or water vapor. Similarly, since metallic titanium under the conditions of temperature required by the Kroll reaction will combine with all gases except those of the inert series, the decomposition of titanium tetrachloride must be done either under greatly reduced pressure or in an atmosphere of such completely chemically inert gases as helium or argon.

DEVELOPMENT OF THE KROLL PROCESS

The Kroll process of 1946 involved a number of difficult and different operations, each of which had to be done on a batch basis. A reaction chamber had to be prepared for each charge. This involved two operations: the chamber had to be closed by means of welding and, after waiting long enough for the contents to cool to atmospheric temperature, the chamber had to be opened by cutting. This led to the loss of the residual heat of both charge and chamber.

The standard way of removing the products of the reaction (roughly one part by volume of titanium sponge intermingled with eight parts of anhydrous magnesium chloride) was by boring out with a machine tool. The chips from this last operation had to be chemically treated in a batch in order to separate the magnesium chloride and leave the titanium as a number of detached particles. These had then to be magnetically treated to remove iron. Finally, the batch application of a powder-metallurgy technique involved heating this sponge for long hours, at a high temperature, in a high vacuum. This gave rise to metal which had to be forged in order to turn it into an engineering material.

The first simplification which has taken place concerns the treatment of the products of the reduction process. Their mechanical boring out and subsequent chemical treatment to remove the anhydrous magnesium chloride has largely been abandoned. When the reaction is complete and the chamber is at about 800 deg. C., time is given for the sponge, anhydrous magnesium chloride and unreacted metallic magnesium to separate under the influence of gravity. While still fluid, they are tapped off. This done, the contents of the hot chamber, now mainly titanium sponge, are subjected to a high vacuum and the remaining magnesium chloride and unreacted magnesium are distilled off. Then, as

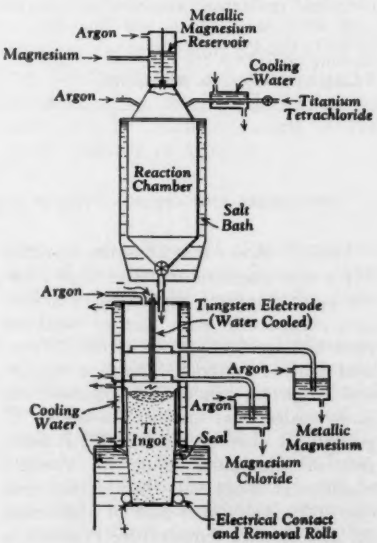
argon is admitted, the chamber is allowed to cool to atmospheric temperature and pressure, when it is opened, the sponge removed and arc- or induction-melted to form ingots.

Probably the bulk of the titanium now available has been produced by such means, but there is no reason to doubt that the Kroll process will cease to be a batch one. Its reaction chamber will be fed, in stoichiometric quantities and without intermission, with molten magnesium and liquid titanium tetrachloride. It will discharge continuously the products of their reaction into an electric arc furnace in which the freshly created particles of titanium will be melted into a coherent whole. The resulting anhydrous magnesium chloride and any unacted magnesium will be distilled off and condensed. The former will be used for electrolytic re-reduction to the metallic state, while the unacted magnesium will be merely returned to the molten magnesium tank from whence, ultimately, it will go back to the reaction chamber.

Such a scheme as this has been considered and tried out by Maddex and Eastwood. Their apparatus is illustrated in the diagram reproduced in Fig. 1. Above the reaction chamber is a vessel containing metallic magnesium at a temperature of 760 deg. C., about 110 deg. C. above its melting point. The pressure head in this part of the unit has to be kept constant by the controlled pumping of molten magnesium from a holding furnace, kept at the appropriate temperature. From the cistern of liquid magnesium, the metal runs into the reaction chamber. Here it meets the titanium tetrachloride. This is fed in at the rate appropriate for carrying out the reaction set out in equation (1). The technical requirements of this chamber are such that reaction is complete when the products of it, solid particles of metallic titanium and liquid ones of anhydrous magnesium chloride, reach its conical bottom, from where they flow through a valve to the next part of the unit.

The dimensions of this reaction chamber must be closely related to the speed of chemical reaction, which is influenced by both pressure and temperature. It therefore follows that both these factors must be kept constant during the operation of the plant. Pressure presents no difficulty; the chamber has merely to be in direct communication with a vessel containing an inert gas, such as argon, which is at an appropriate pressure, 2 to 3 lb. per square inch above that of the atmosphere. The maintenance of a suitable temperature is more difficult since the reaction between metallic magnesium and titanium tetrachloride is exothermic, so that the heat liberated within the chamber, and thus the temperature of the chamber itself, depends on the rate of flow of the reagents into it. This must be strictly controlled and, in order to secure as uniform a thermal condition as possible throughout the whole, Maddex and Eastwood advocate its immersion in a salt bath kept at a steady temperature some-

Fig. 1. PLANT FOR CONTINUOUS PRODUCTION OF TITANIUM INGOTS.



where between 732 deg. and 871 deg. C.

The next portion of the unit is an arc furnace, the design of which presents great difficulties. Not only has it to melt the particles of titanium so that they run together and may be subsequently continuously cast into an ingot; it has to distil, from the mixture which runs into it from the reaction chamber, the anhydrous magnesium chloride and any unreacted metallic magnesium. These two have to be subsequently and separately condensed and, in liquid form, returned to the appropriate parts of the unit.

It is possible that a continuous process may be evolved in which the input will be almost limited to titanium dioxide, coke and electrical energy.

TABLE I.—PHYSICAL CHARACTERISTICS OF PURE TITANIUM, I.E., BETTER THAN 99.9 PERCENT *Ti*.

Atomic number	22
Atomic weight	47.9
Crystalline structure:	
Up to 885 deg. C.	Close-packed-hexagonal
Above 885 deg. C.	Body-centered cubic
Atomic spacing:	
Up to 885 deg. C.	a = 2.950 A°.
	c = 4.683 A°.
Above 885 deg. C.	a = 3.31 A°.
	c = 3.31 A°.
Coefficient of linear expansion	15—730 deg. C., 8.8—9.2 × 10^{-6} per deg. C.
Thermal conductivity	0.036 calories per sq. cm. per cm. per sec. per deg. C.
Specific heat	0.13
Electrical resistance, microhm per cm. per sq. cm.	60
Density, gm. per cc.	4.507
Melting point	1,725 deg. C.
Young's modulus, lb. per sq. in.	15 × 10^6

PROPERTIES AND APPLICATIONS OF PURE AND COMMERCIALLY-PURE TITANIUM

Table I shows that titanium is virtually a non-magnetic metal of high melting point, having a coefficient of expansion comparable with that of steel, an electrical conductivity of about 3.2 percent that of conductivity-grade copper, and a thermal conductivity of about the same order. Its density is about 57 percent of that of steel and 1.7 times that of aluminum, while its Young's modulus is about half that of iron, and one and a half times that of aluminum. At atmospheric temperature titanium is entirely free from corrosion by air or natural waters, including sea water. In the molten state, titanium is intensely chemically active. It combines violently with all gases, other than those of the monatomic series, such as helium and argon. This demands that the metal must be melted and cast in an atmosphere of the kind indicated, or else *in vacuo*. There is no material, metallic or non-metallic, out of which molds can be made with which liquid titanium will not react disastrously.

TABLE II.—RELATIVE WEIGHT AND COST OF TENSION MEMBER

Material	0.2 Per Cent Proof Stress, tons per sq. in.	Density, Lb. per cu. in.	Relative Weight of Tension Member	Cost of Material, Shillings per lb.	Relative Cost of Tension Member
Commercial-grade titanium	33.5	0.16	1.39	106.4	43.5
Aluminum-alloy 75S	29.5	0.101	1.0	3.4	1.0
Magnesium-alloy FS1	16.5	0.064	1.13	7.4	2.5

In the form of annealed sheet, strip, bars, forgings, and so on, the commercially pure titanium can be expected to have at least the following mechanical properties: 0.2 percent proof stress, 33.5 tons per square inch; ultimate tensile stress, 39.0 tons per square inch; elongation, 23 percent. The combination of the mechanical properties and the price which has to be paid for them prompts examination of their relative significance in practical engineering terms.

Consider a tension member made in sheet or strip of commercial-grade titanium (annealed), aluminum alloy 75S, and magnesium alloy FS1, and assume that in each case the working stress would be the same proportion of the 0.2 percent proof stress. The relative costs, deduced from Table II, are as follows: commercial-grade titanium, 43.5; aluminum alloy 75S, 1.0; magnesium alloy FS1, 2.5.

These figures take no account of the respective costs of fabrication. They relate to the simplest type of structural member at atmospheric temperature. By cold work and by alloying, a substantial improvement in the mechanical properties of titanium can be made, but this will not make the cost of a tension member approximate to that of one made in the light-alloy aircraft structural alloys.

Since so many physical considerations are involved in the design of struts and beams, no comparison comparable with the one for a tension member can be made. However, on the rigidity/weight basis, titanium and titanium alloys at atmospheric temperature have a somewhat lower specific rigidity than the older structural alloys.

Although the elastic moduli of titanium can be appreciably raised by alloying (at the sacrifice of some desirable qualities), it appears improbable that the metal will be extensively used for the main structure of aircraft.

FORGINGS

The figures in Table III give the relative price of the material in forgings of titanium, aluminum alloy, and alloy steel. All considerations as to the preparation of the materials for forging, their forging, subsequent machining and heat treatment have been neglected. Such omissions may eliminate the apparent two-to-one advantage shown in favor of nickel-chromium steel. They cannot, however, unfavorably influence the nearly 58 to 1 superiority of the ferrous alloy over commercial-grade titanium, since the cost of the processes applied to titanium greatly transcends that of their application to the older materials.

One fact emerges clearly—at the present stage of its development commercial titanium is not attractive as a material for airframe forgings. What is not so clear is whether it would be technically suitable. The metal belongs to the hexagonal system and therefore it would be expected to have mechanical properties varying with the direction in which they

TABLE III.—RELATIVE COST OF THE MATERIAL IN FORGINGS OF EQUAL STRENGTH MADE IN THREE AIRCRAFT ALLOYS

Material	0.1 per cent Proof Stress, Tons per sq. in.	Density, Lb. per sq. in.	Cost per lb., Shillings	Relative Cost
Commercial-grade titanium	32	0.16	70.5	57.7
Aluminum alloy D.T.D. 683	27	0.101	3.3	2.0
Nickel chromium steel, B.S. S.99	70	0.283	1.5	1.0

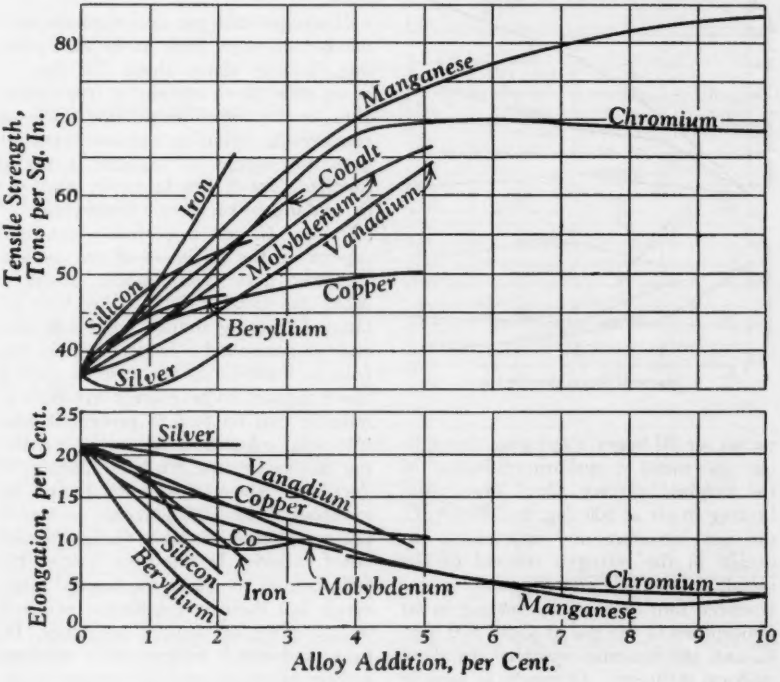
are measured; more evidence is required on this point before one can be sure that, even were titanium cheap, it would also be useful for the purpose under consideration.

There are, however, at least four ways in which commercially pure titanium might well be employed with technical, if not with certain economic, advantage. The author believes that it could be employed in the form of rivets, closeable by cold heading and with, partly as a result of cold work, a pin shear ultimate as high as 35 tons per square inch. Although not yet an article of commerce, titanium tubing with a 0.2 percent proof stress of about 33 tons per square inch and an elongation of over 20 percent has been made. If it can be manufactured with the uniformity of quality required for aircraft hydraulic and pneumatic services, there would certainly appear to be a field of application in this sphere, for its specific proof and ultimate stresses are markedly better than those of such alloys as D.T.D. 310, 328, 503 and T.26. As a fireproof bulkhead, commercial titanium can replace stainless steel with a saving in weight for equal thicknesses of 37 percent. If the oxygen content does not exceed 0.15 percent, that of the nitrogen 0.05 percent and that of the carbon 0.15 percent, the metal is readily welded by an argon-arc technique, which may simplify the making of the bulkhead. Finally, in military aircraft, titanium may be effective as armor, on a weight basis, for it can be surface-hardened by a number of methods which have yet to be tested realistically.

ALLOYS OF TITANIUM

Alloys with Metals.—From a consideration of relative inter-atomic distances, it would be anticipated that the metal would form a solid solution with each of those of Group 1B and of Groups V-VIII of the Periodic Table. Thus, it is metallurgically likely that binary alloys could be made with copper, silver, gold, vanadium, nobium, tantalum, chromium, molybdenum, tungsten, manganese, iron, cobalt and nickel. Experiments have shown that with all these, and certain other elements, alloys can be made. The qualities of many have not yet been fully explored, so it may well be that some have not been correctly evaluated. Fig. 2 indicates the influence of varying amounts of the different elements on the ultimate tensile stress and elongation of the titanium to which it has been added. Most of these produce increases in strength, but, with the single exception of silver, all cause decreases, some startling, in elongation. Simultaneous additions of two or more of some of the metals listed can give

Fig. 2. EFFECT OF ALLOYING ADDITIONS ON TENSILE PROPERTIES OF BINARY TITANIUM ALLOYS.



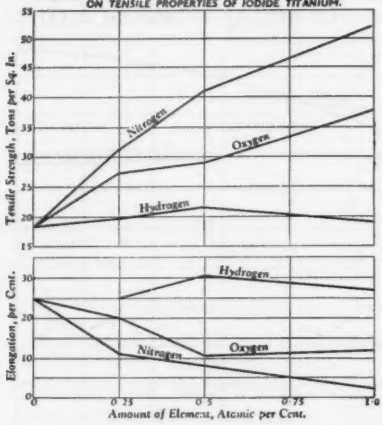
desirable increases of static strength, with a less serious reduction in the ductility than when a single alloying constituent is employed.

Alloys with Gaseous Elements.—Titanium possesses to an outstanding degree the ability to form solid solutions with oxygen, nitrogen and hydrogen. Extremely small quantities of oxygen and nitrogen have a marked influence on the strength of the metal in which they are dissolved. This is clearly shown in Fig. 3, in which the amount of dissolved gas is shown, for the sake of convenience, as an atomic percentage.

The question may be asked: "How can these gases be got into the metal?" In the case of oxygen the most usual mechanism is by diffusion. Titanium-oxygen alloys containing up to more than 5 atomic percent of the gas have been prepared from a piece of thin strip made of iodide titanium having the following determined impurities: oxygen, 0.02 percent by weight, i.e. 0.06 atomic percent; nitrogen, 0.03 percent by weight; iron, 0.02 percent by weight; tin, strong trace; antimony, strong trace; copper, faint trace; silicon, faint trace; vanadium, faint trace; magnesium, faint trace; manganese, faint trace.

The strip was heated in air for several minutes in the range 500 deg. to 750 deg. C. This produced an adherent film of titanium oxide, the thickness of which depended on the length of the heating period. The strip was then heated at 850 deg. to 950 deg. C. *in*

Fig. 3. EFFECT OF ADDITIONS OF GASEOUS ELEMENTS ON TENSILE PROPERTIES OF IODIDE TITANIUM.



vacuo for 30 hours, producing throughout the metal a uniform diffusion of the original surface film. The initial heating in air at 500 deg. to 750 deg. C. did not introduce any appreciable increase in the nitrogen content of the metal. Similarly, nitrogen can be introduced into titanium by heating in an atmosphere of the gas at about 800 deg. C. and subsequently *in vacuo*, to allow uniform diffusion. Although, as seen in Fig. 3, nitrogen is a more powerful strengthening addition to titanium than oxygen, with alloys of equal hardness the cold-working properties of the alloy produced by oxygen additions are better than those of that made by nitrogen ones.

Hydrogen can get into titanium in a number of ways, such as by acid pickling, heating above about 350 deg. C. in an atmosphere containing free hydrogen, or hydrogen containing gaseous compounds, including aqueous vapor. It does not appear to perform a useful function, but it can be easily removed by soaking *in vacuo* at a temperature of 800 deg. C. for a period which will depend on the thickness of the section.

Alloys with Non-Metallic Solids.—Most non-metallic solids alloy with titanium, forming limited solid solutions and/or compounds. Information in this field is limited. In the case of carbon there appears to be enough evidence to indicate that up to 0.25 percent it goes into solid solution in the metal, increasing its tensile strength but reducing its ductility. Above this amount, and up to about 1 to 1.25 percent, carbon is present in titanium as a finely disseminated carbide. In this form it has little influence on the static mechanical properties, but there is insufficient evidence on its effect on impact resistance, fatigue and notch fatigue. For welding, carbon in excess of 0.15 percent is undesirable. As can be seen from Fig. 2, titanium alloys with the metalloid silicon, giving rise to results which are not attractive.

AVAILABLE ALLOYS

Table IV sets out the nominal chemical compositions and some room-temperature mechanical properties of such alloys as are at present commercially obtainable at a price from about 1½ to 2 times that of the pure commercial metal.

Since the proof and ultimate stresses disclosed in Table IV are superior to those of all steels used for aircraft forgings with the exception of S.99, it is at once apparent that titanium alloys give scope for weight economy in the production of forged parts. Experience so far has shown this to be true, but at a monetary cost which may be prohibitive in civil, and even in military, aircraft.

In Table V a comparison is made between the costs of the same forged part, a tank support fitting, made in the American alloy steel 8630, and the titanium forging alloy containing 4 percent aluminum and 4 percent manganese

TABLE IV.—COMPOSITION AND PROPERTIES OF SOME TITANIUM ALLOYS

Constituents Other than Ti	Condition	0.2 Per cent Proof Stress, Tons per sq. in.	Ultimate Stress, Tons per sq. in.	Elongation, Per cent
0.2 Fe, 0.02 N_2, 0.1 O_2	Annealed sheet, bar, forgings	34	39	23
As above	½ hard sheet	42	49	12
1.8 Cr, 0.9 Fe, 0.15 O_2, 0.04 N_2, 0.03 C	Annealed sheet and strip	36	56	19
2.0 Cr, 2.0 Fe, 0.15 O_2, 0.04 N_2, 0.06 C	Annealed sheet, bar, forgings	56	62	14
7 Mn	Sheet	58	63	14
4 Mn, 4 Al	Annealed bar, forgings	60	65	18
2.7 Cr, 1.3 Fe, 0.25 O_2, 0.02 N_2, 0.05 C	As above	58	67*	16*
5.0 Cr, 3 Al, 0.5 C	As above	68	74	10

* Depending on grain size and heat treatment, properties ranging from 90 tons per sq. in. tensile and 6 per cent. elongation down to 60 tons per sq. in. tensile and 30 per cent elongation can be obtained.

TABLE V.—RELATIVE COST ANALYSIS—TANK SUPPORT FITTING

Item	8630 Steel	Titanium Alloy RC 130 B
Weight of rough forging	23.5 lb.	13.8 lb.
Material cost	£2.13	£87.0
Forging	0.67	27.0
Machining	20.60	355.0
Total cost of finished part	£23.40	£470.0
Weight saved	—	5.9 lb.
Cost per lb. weight saved	—	£80

(RC 130B). The figure of 80*l.* is sufficiently startling to require confirmation. This is available in Table VI, in which cost per lb. of weight saved is given for a number of gas-turbine items.

The price which has to be paid in order to save weight is attributable to four causes, one of which is current in experience in forging and machining the new material. Table V shows that at present, the relative costs of a particular titanium alloy part in comparison with an alloy steel one are: material, 41 times as much as the steel; forging, 40 times as much as the steel; machining, 17 times as much as the steel.

Forging.—The fundamental qualities of titanium prevent the adoption of the simplest forging techniques. As mentioned already, titanium, when hot, not only combines with oxygen, nitrogen and hydrogen (whether elemental or not), but this metal/gas alloy film diffuses through the basic matrix, profoundly altering its mechanical properties. Furthermore, in drop-stamping this coating interferes with the flow of the metal in the die. The heating of the forging stock therefore demands control of the chemical composition of the atmosphere of the furnace, the rate of heating and, also, the maximum temperature of the stock, which requires to be low to minimize film or scale formation. On the other hand, the lower the temperature the greater the difficulty in inducing the metal to flow without cracking.

Faced with this dilemma, the practical man has compromised on a range of 880 deg. to 980 deg. C. In this temperature zone, the stock is deformed with more difficulty than would be experienced in forging alloy steel, therefore heavy and expensive plant is desirable. Subsequent to forging, a prolonged anneal at 650 deg. to 700 deg. C. is beneficial. Some of the two-phase alloys, however, are unstable even after such a treatment and subsequently undergo embrittlement if used at temperatures in the range 250 deg. to 450 deg. C.

There is an additional reason for avoiding high temperatures. With the titanium alloys now used for forgings (mainly 2.7 Cr, 1.3 Fe, 0.25 O_2, etc.) grain growth takes place rapidly at high temperatures. This will influence adversely the subsequent room-temperature ductility, impact resistance and fatigue properties of the alloy. Above 1150 deg. C. the oxygen content of those alloys whose mechanical properties depend on the presence of this gas within

TABLE VI.—COST AND WEIGHT ANALYSIS OF STEEL AND TITANIUM-ALLOY GAS-TURBINE PARTS

Item	Material and Approximate Weight of Finished Part in Steel and in Titanium Alloy, Lb.		Approximate Cost of Weight Saving per lb.
Compressor rotor disc	Steel AMS 6342 Titanium alloy	25.0 14.0	£21
Compressor stator blade	Steel AMS 5613 Titanium alloy	0.06 0.04	£62
Turbine support	Steel AMS 6322 Titanium alloy	3.0 2.0	£69
Compressor rotor blade	Steel AMS 5613 Titanium alloy	0.10 0.06	£84

the material tends to decrease, with subsequent decrease in static mechanical properties at room temperature.

Table VI emphasizes how important yet varying, is the influence of machining on the cost of an item. With a simple form such as a rotor disc, the price difference between steel and titanium alloy is relatively low, but with a part of greater complexity, such as a turbine support, the gap broadens markedly. The figures recorded in these two tables are the result of actual experiment by intelligent people well versed in the manufacturing techniques normally employed for making such parts in conventional materials. The cost figures for the titanium alloy arise from the use of established techniques applied to a material with which experience is almost non-existent. Almost certainly both forging and machining costs will be greatly reduced but, in the present state of the art, there are wide differences of opinion as to the best ways of doing this.

ADDITIONAL PROPERTIES

Surface Rubbing.—Titanium and the present titanium alloys have deplorable rubbing properties. The metal is inclined to pick up any other on which it is rubbing. This cold-welding tendency debars the use of the alloy for shafts unless they have a sleeve to provide a rubbing surface in the journals, or unless ball or roller races are fitted. A titanium piston is extremely unlikely to be successful for the present. It is even doubtful if a titanium-alloy nut can be used satisfactory in connection with a bolt of similar composition.

Titanium and its alloys, however, can be given a hard surface by anodizing. If such a coating will not stop galling, or has too ephemeral an existence, then gas case-hardening, produced by heating either in oxygen or nitrogen, can be employed. Failing this, a hard surface can be produced by carburizing. Such experiments are in hand. Under conditions in which contact corrosion is unlikely to arise, a flash coat of copper may be obtained by dipping in a copper-cyanide bath. This may prevent "pick-up." Finally, a chemical treatment, giving rise to an adherent film, can be used satisfactorily in conjunction with molybdenum disulphide, subsequently used as a solid lubricant.

Fatigue.—Unlike practically all the metals of the non-ferrous group, titanium has a true fatigue limit. Results obtained with highly-polished test-pieces show considerable scatter, but it is undoubtedly true to say that the ratio of the fatigue resistance of the metal and of its alloys to their respective tensile strengths exceeds, and sometimes greatly exceeds, one half. Thus the fatigue resistance of this group, in the form of the unrealistic test-pieces already mentioned, is better than that of alloy steels. When, however, notched fatigue test-pieces are used, this is no longer the case. Using test-pieces with and without a severe notch, it has been found that whereas the notched to unnotched endurance ratio for alloy steel specimens was 15 percent, for identical titanium ones made of the 2.7-Cr, 1.3-Fe, 0.25-O_2 alloy, the figure was only one-fifth this amount. In other tests, with a less severe notch (stress concentration factor 2.7), employing the commercially pure alloy, the 10^7-cycle endurance was shown to be only 50 percent of that of the unnotched specimens. These disturbing results have received confirmation from other experiments, but the position is not entirely without hope. It seems possible that, by control of the initial grain size and by close attention to metallographic structure, better resistance may be obtainable when titanium alloys are subjected to tri-axial cyclic stresses. Nevertheless, at present, it has to be admitted that the notched fatigue endurance of such strong titanium alloys as have been tested is poor.

It has been stated that shot-peening does not improve, but considerably reduces, their fatigue limit. It is possible, however, that an improvement may be obtained by a modification of the peening technique. This view is based on the behavior of magnesium (also a hexagonal metal), since, when shot-peening was first applied to its alloys, their fatigue resistance was lowered thereby. Now, however, by a modification of the method, a system of peening has been demonstrated that does in fact raise their fatigue resistance.

Impact Resistance.—So far, the influence on titanium alloys of trace elements, grain size and heat treatment, all very potent in relation to the impact resistance of the ordinary engineering materials, have received insufficient study. It is known that, like the ferritic steels, these alloys are extremely sensitive to temperature. At 300 deg. to 400 deg. C., an Izod impact value of 100 ft.-lb. or more can be obtained. At such a temperature the fracture would be ductile, but at a lower one, which would certainly be above room temperature, it would be wholly brittle. This change in the type of fracture is accompanied by a sharp decrease in impact resistance, but at room temperature, it is probable that the strong titanium alloys, when their chemical compositions and methods of manufacture have become standardized, will possess notched-bar impact values better than those of the current strong wrought-aluminum alloys used in airframe structures, and probably comparable with those of the stronger alloy steels.

Welding.—Reference has been made to the absorption of oxygen and nitrogen when titanium is at a temperature above about 800 deg. C. When its gas content rises, so does its strength, but its ductility decreases. It is because of this that the inert gas type of welding gives the best results. If, however, a weld as strong and as ductile as the parent metal is required, contact of oxygen and nitrogen with the molten and neighboring hot titanium must be prevented. The standard welding torch does this on the working face, but when welding sheet or plate, an inert gas atmosphere must be provided over the hot area on the reverse side of the job.

Roughly speaking, all titanium alloys can be argon or heli-arc welded, but in those which have a two-phase structure, although the tensile strength will be satisfactory, the ductility will be generally extremely low. It may be increased in some cases by subsequent heat treatment. One investigator contends (at present exceptionally) that welds made in two-phase titanium alloys by flash welding possess good ductility. This technique is particularly adapted to repetition work and might well find aircraft-engine applications. Should there be a demand for weldable sheet with a 0.2 percent proof stress of 40 tons per square inch, a tensile strength of about 60 tons per square inch, combined with an elongation of not less than 15 per cent, this is a metallurgical possibility.

Properties at Elevated Temperatures.—The influence of temperature on the mechanical properties of commercially-pure titanium is indicated in Figs. 4 and 5. Both annealed and cold-worked, it is embarrassingly temperature conscious. In alloys of titanium, the metallurgist has succeeded in raising stress levels to a gratifying degree, but his success in reducing the temperature sensitivity of his creations has been somewhat limited; except for short-term uses, a temperature of about 350 deg. C. constitutes the upper limit of their employment.

Some creep figures are available, but creep results are difficult to reproduce. Grain size and very slight variations in chemical composition have considerable influence on the creep rate of alloys to the same specification. In Fig. 6, the superior resistance to creep of two titanium alloys to that of the commercially-pure metal is shown. Once again the temperature sensitivity of the three

TENSILE PROPERTIES AT ELEVATED TEMPERATURES OF ARC-MELTED COMMERCIAL-PURITY TITANIUM.

Fig. 4.

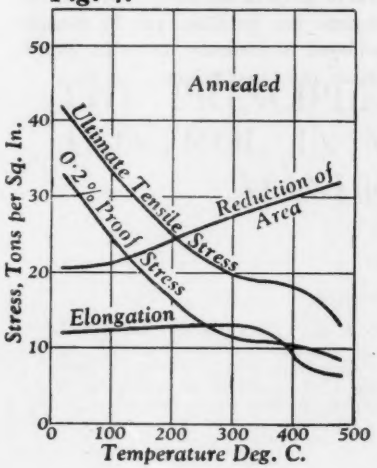


Fig. 5.

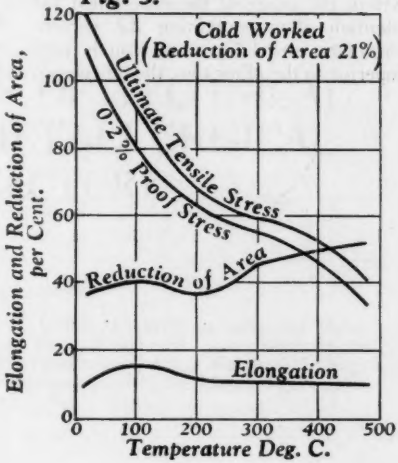


Fig. 6.
INFLUENCE OF TEMPERATURE ON CREEP OF TITANIUM AND TITANIUM ALLOYS.

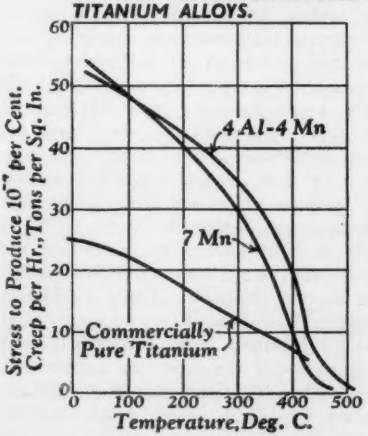
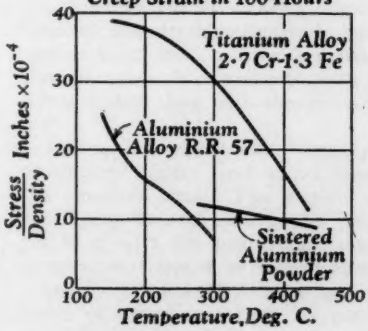


Fig. 7.
COMPARISON OF MATERIALS FOR AXIAL COMPRESSOR BLADES.

Variation in Specific Stress with Temp. Required to Produce 0·1 per Cent. Total Creep Strain in 100 Hours



materials is emphasized. In Fig. 7, relative specific creep rates of three materials used for axial-compressor blades are shown. While at all temperatures within the range of the experiment the titanium alloy containing 2.7 percent chromium and 1.3 percent iron is very superior to the other two, the downward slope of its specific creep curve is impressive. On the basis of a considerable body of evidence available, the upper limit of temperature above which neither titanium nor its alloys can be usefully employed is, contrary to earlier expectations, of modest height.

THE PRINCIPLES OF TECHNICAL CONTROL IN METALLURGICAL MANUFACTURE

ACKNOWLEDGMENTS

This paper was written by DR. A. R. E. SINGER, Lecturer in Industrial Metallurgy, University of Birmingham. It was the lead paper in a symposium on the control of quality in the production of wrought non-ferrous metals and alloys, held in London on 25 March 1953, and was published in the March 1953 edition of "The Journal of the Institute of Metals."

I.—INTRODUCTION

The science of technical control of quality in manufacture has an underlying unity that is revealed only by careful analysis. Its applications are widespread, for it embraces the control of raw materials, processes, and manufactured products in the factory, as well as the methods whereby control is effected. Despite this wide coverage, there is a coherent body of knowledge dealing with the subject, and a number of important principles can be seen to run throughout. Whenever the subject of technical control of quality is mentioned, the techniques of control used in the factory immediately spring to mind. Inevitably, a greater attention is paid to them than to the fundamental principles, which are often assumed to be self-evident and scarcely worth enunciating. It is appropriate, therefore, to examine on a broad basis the main factors affecting control. This is particularly desirable because the subject is one on which a great deal of research and development work is being done. Much of the work is concerned with only a small part of the total field, yet the same basic factors are operating throughout, and the accumulated experience from one part may be of great help in another. It is necessary in these circumstances to take an overall view of the situation, put the various pieces of research and development work into a correct perspective, and to formulate a plan of action in conformity with the whole rather than with the individual parts.

The science of control of quality is developing rapidly, and at no time is the situation static. The pattern will not repeat itself exactly in the future, yet it is with the near future that a progressive scientist or industrialist is primarily concerned. A mere accumulation of experiences from the past is of little use for planning action in a changed future, and the only way to resolve the difficulty is to extract prin-

ciples from present and past experience and use them as a guide for the further development of processes and techniques. Experience has shown that principles are more persistent in time than practice, and a good deal more reliable. The purpose of this paper, therefore, is to outline some of the underlying factors operative in the technical control of quality and where possible to deduce from them promising lines for future research and development.

The technical control of processes is not an end in itself. It should always be carried out for a specific purpose in order to achieve certain desired results, and it is very revealing to examine more closely what these results are. It would be generally accepted that high quality in a product is desirable and the higher the better. Unfortunately, the attainment of quality is directly related to cost, either because of higher cost of the materials, machines, and labor, or because of additional charges required for accumulating knowledge and carrying out research and development necessary for the manufacture of the product. In addition, the mere setting up of a system of control inevitably causes additional expenditure of money, and this again must be put on the debit side of the account. Under the heading "The Economic Aspect" (Section III), the problem will be examined in greater detail, but it soon becomes apparent that at any one time within a concern there is an optimum standard of quality for a product, and control of quality in the region of this standard is economically desirable.

The economic aspect cannot be left out of any comprehensive picture of control. In fact, it becomes an essential function of management to measure the success or failure of a system of control by relating the results achieved to the new total cost of the product. While this view would generally be conceded when the point is emphasized, it is not always kept clearly in mind. Frequently it happens in industry that schemes of instrumentation or recording are embarked upon, apparently for their own sake, with only a vague and rather hopeful picture of how the quality of the product or the economy of production will be affected. Such a state of affairs cannot be described as control, and any steps taken to define accurately the purpose of control in relation to quality and the reasons for its installation would be invaluable.

II.—QUALITY AND ITS MEASUREMENT

The word quality is a simple one describing a complex state that is difficult to interpret. There are two concepts of quality, not incompatible, but often leading to a confusion of thought. In the first place quality may be thought of as being measured on a scale leading to an objective perfection without relation to uses or applications. Secondly, the quality of a product may be linked with its ultimate use, in which case the criterion is fitness for purpose. If either of these definitions is adhered to rigidly, then difficulties of interpretation may occur. But the two concepts are not contradictory, and when it is realized that in the case of metallurgical manufacture an ideal standard is set by the purpose for which the product is intended, then the difficulty is resolved. Thus the standard might be complete freedom from porosity, which in the case of a casting would be unattainable. Alternatively, the standard might be a particular thickness for strip material, which in practice would never be attained exactly.

This leads directly to the question of how quality can be measured. In a great many cases no simple method of physical measurement is available, and in its absence the best that can be done is to set up certain standard examples and use them for making comparisons, classifying the products on the basis of the unaided judgment of the inspector. Such

methods are unsatisfactory from a scientific point of view, but have to be applied at least in part with such features as surface finish, defects and blemishes of all kinds, porosity, segregation, and internal cleanliness of castings. Gradually more and more of these features are becoming amenable to physical measurement, and part of the answer to the problem may be a closer analysis of the situation, so that, for example, in the case of porosity and segregation, its location and dispersion are taken into account as well as effects of density or chemical composition.

Where it is possible to make physical measurements relating to quality, much more can be done by way of interpretation, and it is on this basis that it is now proposed to deal with the concept of quality. Suppose we take a simple example of strip metal being produced for subsequent deep drawing. The quality of the strip will then be a function of its chemical composition, metallurgical structure and properties, its surface condition, and its dimensions, especially its thickness. All these quantities, except surface quality, can be measured with precision, but for the present purpose only the thickness need be considered, as a similar state of affairs pertains with the others. This aspect of quality is important because of the clearances between the tool and die. It will be a maximum at one particular thickness or ideal dimension, X_i, and in the ideal case strip would be produced at this size. However, this is a counsel of perfection not attainable in practice, and this is recognized by manufacturing to certain tolerances, say, $X_i \pm 0.003$ in. This means that quality falls as the thickness departs from X_i, and at any point beyond $X_i + 0.003$ or $X_i - 0.003$ in. is no longer acceptable. The best index of quality for an individual article is then the nearness of the strip to the standard expressed as a number. Similar criteria can, of course, be used for all the other quantities involved, except surface finish. In the case of a group of such strips the best measure of this aspect of quality would be the arithmetic mean $\overline{X}$ of the dimensions or quality characteristics of the individuals taken in conjunction with their standard deviation σ. Such objective standards of quality are an immense aid to everyone in the factory, as they enable operators and inspectors to detect any deterioration with the maximum speed and certainty, and permit corrective action to be taken at the earliest moment. This is the essence of control of quality, and it greatly simplifies the work of the technical officer in charge if numerical values and limits can be provided to which he can work.

III.—THE ECONOMIC ASPECT

It has already been shown that for any given process, quality of product and cost of production tend to be mutually opposed, so that in practice some compromise solution must be sought. The question immediately arising is that of choosing how much of each to aim for. The situation is necessarily tied to the overall economy of the process and may be clarified by considering in diagrammatic form the cost of manufacture of a product as compared with its value to the consumer in terms of its usefulness. Here we are not concerned with the other aspects of value related to cost, esteem, or exchange.

If it is assumed that quality can be measured on a physical scale—in this example as an approach to an ideal dimension—then a value/quality diagram might take on a form such as that shown in Fig. 1. The curve V will usually flatten out as the ideal dimension is reached at X_i and will be zero at some point B, where the maximum acceptance tolerance for the article is reached. Such a value curve would refer to individual items of product at the

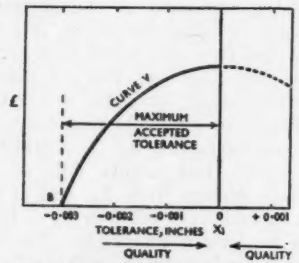


FIG. 1.—Value/Quality Relationship for Individual Items Produced.

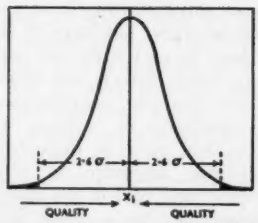


FIG. 2.—Frequency Distribution Curve for Varying Tolerances.

exact dimensions indicated in the diagram. When applied to a productive process, the situation becomes more complex because it is not possible to manufacture at specific dimensions, and tolerances must be allowed. If the manufacturing process is considered alone and there is no subsequent inspection of the product, then the frequency with which each quality of product occurs will in the general case follow a binomial distribution. In any process some defective items of product will always be made, and the manufacturing limits that can be held will depend on the proportion of defective items that can be tolerated in the output. With a normal frequency distribution, as shown in Fig. 2, and a proportion of defectives of, say, 1%, the tolerances will be $\pm$ 2.6σ, where σ is the standard deviation for the process. On this assumption it is possible to draw both value and cost-of-production curves for manufacturing processes of varying degrees of precision, i.e. of varying σ. The curves may now take on the form shown in Fig. 3, where curve V is the value in pounds sterling of an individual item of those exact dimensions, as in Fig. 1. Curve A will then give the value of a product in which 1% of the output is defective or outside the manufacturing tolerances $\pm$ 2.6σ. The curve will again flatten out at the ideal dimension and will be steep where it cuts the axis at D. At this point the value will be zero because of the large proportion of unacceptable material it contains—in this case about 2.3σ or 3%.

A further curve C, showing the cost of production by the process such that only 1% of defectives are produced at any particular tolerance, can now be inserted. Such a cost-of-production curve will always rise steeply as the ideal dimension is approached and tolerances are narrowed, and will tend to a definite value in pounds sterling as tolerances are widened. It should be noted that curves V and A are hypothetical, in the sense that in practice it is possible to make only rough estimates of value at various qualities, but curve C can sometimes be drawn with fair accuracy. Furthermore, all the curves are drawn for one given state of technical knowledge and skill. As this improves with time, so curve C moves downwards and closer to the vertical axis at X_i, but at the same time, owing to competition in the industrial field, curves V and A tend to move in the same direction, so that the general pattern remains similar.

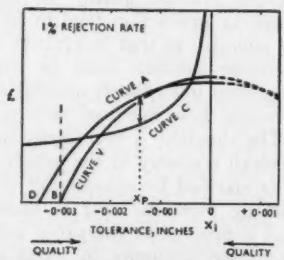


FIG. 3.—Value/Quality Relationship for Products Containing 1% of Defective Items.

On the basis of the curves in Fig. 3, the point at which it is most profitable to manufacture is at X_p, where the value/cost-of-production loop is deepest. In other words, there is an optimum quality having tolerances of $\pm X_p$ where production should be held, and any departure from these tolerances with a rejection rate of 1% would lead to a decrease in profitability. If the two curves A and C did not intersect, then of course all production would be made at a loss.

Thus the curves, even though hypothetical in character, do succeed in illustrating the important point that ultimate economy dictates that at any one time in a manufacturing process the quality of the product should be controlled at one particular value, and that any divergence from this value will carry with it economic penalties. Here is a basic reason for the control of manufacturing processes.

It can be shown in a similar manner that for any process that is operating to fixed tolerances there is an optimum rate of rejection at which the cost of production per unit of acceptable product is a minimum. Such a curve might take the form shown in Fig. 4. The curves in Figs. 2 and 3 were, of course, drawn for a fixed rejection rate of 1%, but similar curves would have been obtained at any other rate. In any instance in practice there is a best rejection rate, or range of rates for a process, and efforts should be made to reach this rate rather than merely to reduce rejections to a minimum.

Mention has already been made of the fact that improvement in quality of a product can be made in two principal ways. In the first place it can be achieved by raising the quality of raw materials, reducing tolerances by employing more skilled labor and supervision or machines of higher accuracy, and by more rigorous inspection methods. The other way of achieving higher quality in a product is to utilize scientific investigation with the object of finding better methods of manufacture. Both methods carry with them financial penalties, but there are important distinctions to be made between them.

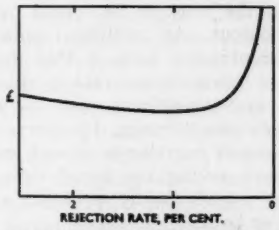


FIG. 4.—Cost of Production/Rejection Rate Relationship per Item of Acceptable Product.

The first method has as its principal advantage that of simplicity and the small time-factor involved. In response to an alteration in demand, it is usually possible to raise quality by this means within a short period, and the increase in cost of manufacture is then given by curve C in Fig. 3. The situation, however, is a static one, and the increase in cost is payable on every item of product made, however long production continues and, as a first approximation, however many are made. In contrast, the method of scientific investigation achieves more lasting benefits. It is true that again a price has to be paid for quality in terms of costly research, development, and design, but once the work is done it is applicable to all the items of product manufactured, and the cost of investigation can be borne by indefinitely large numbers of the product. In addition, such work is cumulative, and one research worker starts building at the point at which another has left off. The situation is thus essentially a dynamic one, and a continual advancement in quality is the result.

The immediate disadvantages attached to such a method of improving quality are twofold. There is the time element to be considered, for research and development work is necessarily a lengthy process, and there is the need for the

cost of the work to be spread over a large output. An additional point, of local significance only, is that the results of research are rapidly disseminated, and competitors soon use them to their own advantage. However, there is a constant interchange of such knowledge and, taking the broad view, the process is undoubtedly of benefit to the world at large.

The two ways of improving quality always proceed simultaneously, and it is virtually impossible to operate one without some intrusion by the other. The important thing is the emphasis given to each. The experience of the last two decades has brought out clearly the big advantages of the research method, and all indications are that in the future this will increase still further in importance. The present series of papers dealing with the control of quality in metallurgical manufacture is a significant step in this direction.

IV.—CONTROL AND ITS IMPLICATIONS

A definition of a controlled system given by Shewhart (1) can be used as a basis for further development. Shewhart's definition is as follows: "A phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon may be expected to vary in the future. Here it is understood that prediction within limits means that we can state, at least approximately, the probability that the observed phenomenon will fall within the given limits."

It is characteristic of machines and processes not subject to control, either automatically or by a human operator, that they will not continue of themselves to give a product of constant quality. After a time a discrepancy between the required and the actual quality value makes an appearance and can be called the "error". In any manufacturing process many variables will be operating at any one time, but to simplify the analysis, we can suppose that each variable, with the error derived from it, is being considered by itself. The reason for the appearance of an error will then be twofold. One part of the error will have a recognizable pattern and will be attributable to a maladjustment of a known factor in the process. This cause of error can be termed an "assignable" cause, and action can be taken to correct the error by adjusting the cause of it. In many cases a correction can be made even though the cause is unknown, provided that the error has a recognizable orderly pattern and a means of correcting it is known. The other part of the error will not have a recognizable pattern, and will presumably be brought about by unknown factors operating in what is apparently an irregular manner. These causes of error can be termed "non-assignable," and although they may be treated by the statistical laws governing chance variations, no action can be taken to correct them.

The main problem confronting the control engineer is how to ensure, when an error not due to non-assignable causes is detected, that action is taken to reduce it. The recognition of errors having a regular pattern due to assignable causes, as opposed to those due to chance fluctuations (non-assignable causes) is not easy. In the first instance, therefore, it is best to consider the simple case where a succession of articles is being produced and the error indicated is an integrated effect such that chance fluctuations do not make a significant contribution.

The way in which control is effected is by arranging for the error to set in action a mechanism that will lead to a reduction of the error. In other words, a compensating system is set up that is error-actuated, and this may be done wholly automatically or through a human operator. There is thus a clear

distinction between a cycle of operations that is predetermined and rigid, and one that is error-actuated and not pre-determined in its action. However complicated the first may be (e.g. the mechanism of an automatic gramophone-record changer), it is not a controlled cycle. For true control it is essential to have a closed-loop or feed-back system, as in the second case, and a way of correcting the error must be known and the necessary action taken before control can be effective.

Turning to the practical aspect of process control, it is convenient to take as an example the case of a product already in manufacture, on which technical control of quality has hitherto been a haphazard and arbitrary affair. The various steps to be taken to ensure adequate control can then be clearly brought out. The first step is to find out the major factors affecting the quality of the product in order to determine how, and to what extent, they affect it. This investigational stage is one of the biggest jobs in technical control, and may consume a large proportion of the time of trained scientific staff. The work, although lengthy and expensive, would employ normal scientific procedure for investigation, and should reveal assignable causes of variation in the quality of the product. But in every instance there are bound to be variations in manufacture that at any given state of knowledge cannot be tied to a particular cause. Some of these may show a regular and persistent pattern of behavior, and can usually be related to some aspect of the process, in which case they can be placed in the category of assignable causes. The remainder can be termed non-assignable causes of variation. These variations are then best treated as random events following the statistical laws governing chance fluctuations. If these laws are not closely followed, then evidence is immediately provided by means of which the operating cause may be recognized and placed in the assignable category.

The investigation of causes of variation, their separation into assignable and non-assignable classes, and the relating of effect to cause is absolutely essential, and must be carried out before process control is established. Failure to do this is bound to lead to disappointment in the results of process control, and if the analysis of the process is unsatisfactory in this respect it is best to recognize immediately the grave limitations it will place on the effectiveness of control. In the metallurgical field this is generally realized, and a large proportion of the applied research effort is expended on obtaining a fuller understanding of manufacturing processes, and in particular the effect of manufacturing variables on the properties of the product. Such effort is well directed, but it should be recalled that the research is not an end in itself and is only of value and can be justified only when it is used for effectively controlling the manufacturing processes.

The next stage in controlling the quality of a product during manufacture is to set up standards by defining the tolerances or limits within which the product may vary and yet remain acceptable. At the same time it is advisable to assign the corresponding limits to the factors causing or correcting the variations in quality. Whenever possible, such limits should be subject to physical measurement and expressed numerically. This stage is an important one for management because, as stated earlier, it involves a critical analysis of data on costs, yield, etc. The standards may be arrived at on a statistical basis or, more frequently, by a common-sense assessment of the position. The essential part of the process, however, is the setting up of standards and the defining of tolerances; once this is done control can be established. At this stage the method of control to be used has to be considered, and a number of different ones are available, each with its own

characteristics. Four main methods, automatic control, control by human operator, statistical control, and operational research, will be considered here.

V.—AUTOMATIC CONTROL

It is simplest in the first instance to consider control systems involving mechanisms only, and then later to extend the general principles to cover the more complex case of a control system involving a human operator. A definition of control was given earlier, from which it appeared that an essential part was the indication of an error between the expected and the actual performance, followed by action to reduce the error. In the case of automatic control this is performed by a mechanism, and it is necessarily implied that some physical indication or measurement of the controlled variable is available. The field of application of automatic control is therefore limited at the moment to systems in which physical measurement of the variables can be made. However, within this field automatic mechanisms have revolutionized the outlook for process control, and complex problems involving the analysis of data relating to several variables can be solved quickly and reliably.

It might at first be thought that if the measurement of error was sufficiently sensitive, the construction of a system giving control within the required limits would be a simple affair. Yet when considered in detail it becomes clear that a stable and accurate system of control is dependent on a number of factors such as time, capacity, and transfer lags. It is not appropriate here to enter into the technicalities of automatic control, and indeed the published literature on the subject is immense (2-4), but a brief note of some of the problems associated with automatic mechanisms is useful, especially as many of them apply equally to human operators.

1. *Automatic Control of Plant and Processes.*

In all automatic control mechanisms a measuring or indicating unit is required for each variable being controlled. If we limit consideration to the control of a single variable, then we shall require in addition a regulating unit capable of effecting a change in the controlled variable and, connecting the two, a controlling unit that operates the regulating unit in response to the signal given by the measuring unit. The system is thus a closed loop of the type shown in Fig. 5. It is interesting to note that, although this type of control is accepted nowadays with scarcely a thought, it is of fairly recent origin, and until a short while ago metering of plant was used solely for performance and accounting purposes.

The signal from the meter (M), and therefore the input to the controller (C), is usually a weak one, and will need amplification and modification before it can be used satisfactorily for operating the regulating unit (R). The way in which this is done determines the performance of the controlled system, and is the chief problem in the design of automatic control mechanisms. The application of automatic control to production processes in metallurgical industry differs from the more usual engineering applications in that the time element is much more extended. For instance, an automatic pilot of an aeroplane is designed to correct errors of flight in short periods of time, whereas in many process-control applications the

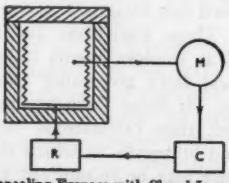


FIG. 5.—Annealing Furnace with Closed-Loop Automatic Control.

correction of an error may occupy many minutes or even many hours. The chief reasons for this difference lie in the magnitude and importance of transfer lags and capacity lags associated with production processes. The time lags occurring between the metering of the controlled variable and the operation of the regulator are relatively small and unimportant, as this connection is usually made electrically.

The effect of a capacity lag on a control system is clearly brought out in diagrammatic form in Fig. 6, where a step change in the controlled variable is caused by the addition of a metal charge to a temperature-controlled salt bath. It is assumed that the system is provided with an "ideal" two-position controller and that the heating elements immersed in the salt have a small thermal capacity. Because of the thermal capacity of the salt, a fall in temperature, although followed immediately by heat input from the immersed heaters, will not be corrected for an appreciable period of time, and control will be deficient to this extent.

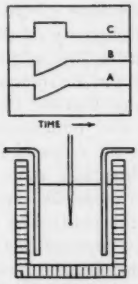


FIG. 6.—Temperature-Controlled Salt Bath, Showing Capacity Lag.
A = Temperature of bath.
B = Input to controller.
C = Output of regulator.

A transfer lag is illustrated in Fig. 7 by a rolling mill whose screw-down gear is automatically operated through a proportional controller by a gage measuring the thickness of the rolled strip. In this case the gage is separated from the rolls by a short distance, so that there is a time interval between the rolling and the measuring of any particular part of the strip. A step change in the thickness of the ingoing strip will cause an increase in the outgoing thickness because of the elasticity of the rolls and housings, but the change will not register on the meter, and corrective action will not begin for a finite period of time because of the transfer lag. Then, provided that the lag is not too great compared with the rate of operation of the screw-down motor, the thickness of the strip will gradually be rectified. The transfer lag, together with its deleterious effects on quality, may of course be reduced by decreasing the distance between the rolls and the thickness gage, or it may be eliminated altogether by the method of Hessenberg and Sims (5), using the rolling load at a constant roll setting as a measure of outgoing thickness.

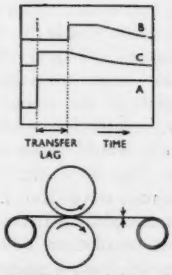


FIG. 7.—Rolling Mill Fitted with Gauge Control, Showing Transfer Lag.
A = Ingoing thickness.
B = Meter reading.
C = Outgoing thickness.

The third example (Fig. 8) shows the effect of a step change in the temperature of a crucible of molten metal on a system having a single capacity lag and a thermal resistance. Here it is assumed that the furnace has a negligible heat capacity and that the system is fitted with a proportional controller. The step change in temperature causes an immediate input of current into the heating elements, but because of the

thermal resistance of the crucible and the thermal capacity of the metal, there is a perceptible lag in the rise in temperature of the thermocouple. After a time, provided that the heat input is not too great, the temperature will once more attain the original level.

Fig. 9 illustrates some characteristic responses of controlled systems to a step change in the controlled variable. The fully damped reponse in (*a*) approaches the ideal and bears some similarity to that of Fig. 6, but the same system fitted with a proportional controller would give the characteristics of (*b*). The damped oscillations of (*c*) are a common effect, and are permissible for many industrial purposes. The hunting response of (*d*) would be given by the system shown in Fig. 7, if the transfer lag was too large in relation to the rate of operation of the screw-down motor. Similarly, cumulative oscillations, as in Fig. 9 (*e*), would occur in the system shown in Fig. 8, if the heat input to the elements were too high and the heat capacity of the furnace appreciable. At all cost, oscillations of this type must be eliminated from a system of control.

The type of controlling and regulating unit has to be chosen carefully so as to give the most effective control of the system. If the output from the regulating unit could be made instantaneously equal and opposite to the error, then the error would vanish and control would be ideal. As we have seen, various lags make this impossible, and the best that can be done is to correct the error as quickly and effectively as possible. By further amplification of the signal received from the meter, the output of the regulator, and therefore the

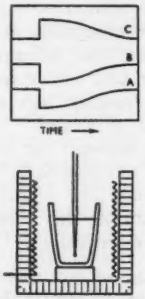


FIG. 8.—Controlled System with Capacity Lag and Thermal Resistance.
A = Temperature of metal.
B = Input to controller.
C = Output of regulator.

rate of correction of the error can be increased. But for a given set of lags the amplification that can be used is limited, because beyond a certain point over-correction exceeds the original error and an unstable condition is set up in which cumulative oscillations occur. The system is then wholly out of control and the amplitude of the oscillations will increase until limited by some other factor in the process.

The types and characteristics of automatic control units used for ensuring the best result in any given situation are not pertinent to this paper, although they form the hard core of control engineering. Suffice it to say that nowadays types of control unit are available to serve most of the needs of metallurgical processes. The limiting factor is usually in some other part of the control system. The conclusion is, therefore, that the characteristics of a process and of a control unit have to be considered together and must be carefully matched to give a product of good and consist-

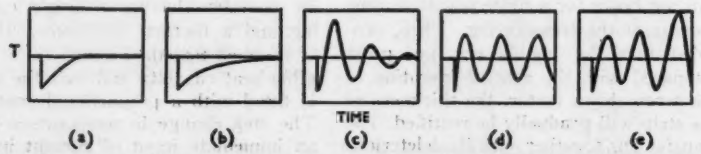


FIG. 9.—Responses of Controlled Systems to a Step Change in the Controlled Variable.

ent quality. Neither, considered separately, is likely to yield good results and, as we have seen, it frequently happens that the characteristics of a piece of plant are such that no control unit can give it a satisfactory performance.

2. *Control of Primary and Secondary Variables*

One important factor applying forcibly to metallurgical process control is rarely given sufficient attention in the technical literature. In concerns what may be called the primary and secondary variables in a control system. Suppose we take the case of a continuous annealing furnace used for the annealing of metal strip, the temperature of the furnace being controlled automatically by an efficient controller. We can then assume that the temperature of the strip is raised to a prearranged value and is allowed to remain there for a known period of time. It follows that if the original strip was of the correct composition, structure, and condition before annealing, it will possess the expected properties afterwards. The important point here is that the ultimate requirement is annealed strip with a certain structure and properties, whereas the variable being controlled is temperature. Putting the situation in diagrammatic form, as in Fig. 10, it is apparent that the primary variable—the structure and properties of the strip—does not form part of the closed loop and is not controlled directly. This state of affairs can clearly be distinguished from the true control of a primary variable, as in the control of thickness of metal strip during rolling by altering the front tension applied(5). Here the strip thickness is measured directly and forms part of the control loop.

The control of a primary variable is a much more satisfactory procedure, because if it is fully operative, then variations in the ingoing material are possible without seriously affecting the product. Thus, in the rolling-mill example in Fig. 11, within certain limits

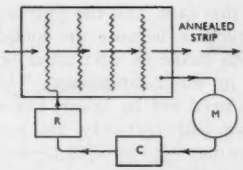


FIG. 10.—Control of Secondary Variable During Continuous Annealing of Strip.

the gage of the product is controlled irrespective of the variations of the ingoing strip, provided these are not too great. In the case of the annealing treatment under consideration we have an entirely different picture, for here it is essential to the formation of a uniform product that the ingoing strip be standardized. In other words, the structure and properties of the ingoing strip itself must be maintained within fine limits. This process may have to be pushed back still further in the sequence of processes, and eventually we may have to manufacture to fine limits throughout—a very costly and time-consuming business. The control of a secondary variable does tend to have this effect in manufacture, so that whenever possible it is best to introduce the variable which it is wished to control into the control loop. A further consequence is that when controlling a secondary variable there is no direct indication that the primary variable is being maintained at the required value, and some additional independent measurement is necessary. Even more important is the fact that for success with this type of control it is imperative that there should be a fixed and definite relationship between the secondary variable, tempera-

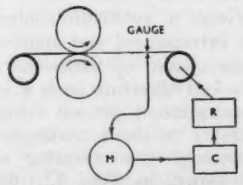


FIG. 11.—Control of Primary Variable During Continuous Rolling of Strip.

ture in this case, and the primary variable, structure, because the controller is unable to make a correction for any change in the relationship. The relationship need not be linear, but it must be known with certainty, and auxiliary variables may also have to be controlled within fine limits to prevent undesirable disturbances being carried into the main control system. Later it will be shown that in spite of the obvious advantages of controlling primary variables, little progress in this direction has been made in metallurgical industry. This is both a challenge to and an opportunity for metallurgists.

VI.—CONTROL INVOLVING A HUMAN OPERATOR

Many of the principles of automatic control apply equally to control by a human operator. Where the work is purely mechanical, it is desirable from both an ethical and a material viewpoint to replace the human operator by a control mechanism. Automatic mechanisms come into their own when speeds of operation are high and time intervals short, but in a great number of process-control applications the time intervals involved are long and the situations complex. In many of these instances, ranging from the technical control of a small manufacturing variable to the managerial control of a works, it becomes advisable to employ a human operator. This is always true when the quantities are not measurable by physical means, or when the number of variables concerned is too great and their inter-relation too complex for automatic control, as in the last case. It is in connection with the simultaneous operation of a number of variables that the frailty of human judgment is brought out most clearly, and later we shall see that statistical methods of analysis and operational research methods may help us to make wiser decisions.

A good deal of light is thrown on the behavior of a human operator when the characteristics of automatic control systems are extrapolated and applied to a closed-loop system of which he forms part. We can illustrate such a system by the independent process inspection of the quality of sheets produced by a simple two-high non-reversing rolling mill, as shown in Fig. 12. Several equivalences immediately appear. The transfer and metering lags correspond to the delay between the rolling of the sheets and their inspection, and to the time taken by the inspector to arrive at a decision, respectively. Any persistent errors occurring during this period will lead to a quantity of bad product proportional to the lag, which must therefore be kept to a minimum, as with automatic systems. Where inspection is carried out in a haphazard manner, the lag is likely to be extended and may involve a prolonged post-mortem of many subsequent manufacturing processes before the trouble can be diagnosed and corrected.

Very frequently the inspection or measurement of an item of product can be used only for the correction of error on subsequent ones. This follows either from the time lags mentioned above or from the destruction of the article during inspection. During batch production the facts have to be faced that the maximum amount of information for control purposes is not being obtained and that the results of poor control are more serious numerically than with continuous production. For these reasons alone continuous production is more amenable to control and will generally give a higher yield of uniformly good product. Any delay between the discovery of a persistent error by the inspector and action being taken by the mill operator to reduce the error, will correspond to a time lag in the control and regulating part of an automatic system. Unless the organization is such that the transmission of information to the foreman and of an order to the mill operator can be

effected quickly, then an appreciable output of bad work will occur.

If we now consider the overall characteristics of controlled systems we again find a number of parallels. It is essential for the process operator to know exactly how, and how much, to correct for a given error detected by the inspector. Such a correction will generally be of a step type, and two difficulties are likely to arise, the first due to a faulty correction and the second due to chance fluctuations. Under-correction may continue to yield a poor product, but over-correction may be worse, for the initial cycles of the unstable system illustrated in Fig. 9 (*e*) may appear. Chance fluctuations always play some part in industrial processes, and due allowance must be made for them if control is to be effective. A situation where the normal run of product varies in a random manner is illustrated in Fig. 13. If the tolerances are set at the low value of $\pm 2\sigma$, then we must expect approximately 1 in 20 of the products to be outside the tolerances. No special significance is to be attached to *A*, and no control action should be taken on such an isolated example. If a correction were made on the evidence of *A*, then point *B* would be out of tolerance, together with many subsequent ones. There are two ways of treating the problem. The more usual one is the common-sense way of waiting for an arbitrary number of readings to confirm a change in the process, but the problem may be tackled on a statistical basis with considerably more confidence and accuracy.

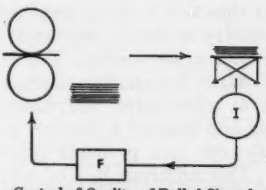


FIG. 12.—Control of Quality of Rolled Sheet by Human Operator.
I = Inspector. *F* = Foreman.

The example first given related to a simple manufacturing process, but the principle is equally applicable to the control of a department or works. Lack of knowledge of how to correct errors, or delay in detecting and correcting them because of poor supervision or procrastination, allows a situation to get out of control. When action is taken, it is often a desperate measure leading to heavy over-correction as shown in Fig. 9 (*d*) and (*e*). Unfortunately, examples of this are familiar to everyone in industry, when affairs proceed from one crisis to another with monotonous regularity and lead to a general deterioration of morale and lowering of output. Such a situation is essentially related to that described above, and the cure for it is similar.

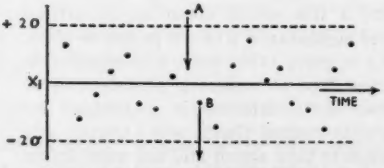


FIG. 13.—Random Distribution of Quality Values.

VII.—STATISTICAL CONTROL OF QUALITY

The particular feature of statistical control of quality is the recognition of the part played by chance fluctuations in manufacturing operations. It contains a procedure for dealing with them and reaching definite conclusions on action despite their occurrence The fact that the statistical method makes allowance for chance happenings enables it to extract the maximum amount of legitimate information from data supplied by the meter in a control system. Consequently, it leads to the most efficient form of control, provided that the time

interval allowable between metering and the necessary action is sufficiently long for the data to be studied. The admission of chance has another effect, namely that of eliminating the illusion of certainty and making it possible to predict only the best probable course of action. This apparent loss of certainty is unimportant, as uncertainty is inherent in the nature of the data supplied. It merely shows up clearly in a statistical analysis and is not derived from it. Moreover, the degree of uncertainty can be reduced at will by taking a greater number of observations, and in each case the probability of error can be estimated. From a technical point of view statistical control of quality is evidently desirable wherever it can be operated. There is, however, the total economy of the process to be considered, for the installation of a system of statistical quality control means an initial increase in overheads, at least during the change-over period. This aspect cannot appropriately be dealt with here, except to note that it is an important managerial responsibility to decide whether or not the benefits derived from the more efficient control are sufficient to justify its installation.

The quality-control chart is now a familiar sight in metallurgical industry, and a few words about its limitations and significance will not be out of place. As in every other case, it is essential to know how to reduce a persistent error once it is detected in a system, for quality-control charts will indicate only when to take action and not what action to take. Similarly, it is necessary to distinguish the assignable causes of variation in quality so that they may be used for control purposes. The non-assignable causes of random variation are then treated in a statistical manner, and action is predicted on this basis.

Suppose we take a simple case where one variable is being controlled by individual meter readings and chance fluctuations are occurring. Then, for a given state of control at a value X_i, assuming a normal distribution, we can draw a diagram of the type shown in Fig. 2, giving the frequency with which each value of X occurs owing to chance causes. The diagram immediately shows the proportion of product falling within any given tolerances, as in Table I, so that the value of A in Fig. 13 is not surprising even though the system is under full control. The effectiveness of

TABLE I.—REJECTION RATES AT GIVEN VALUES IN TERMS OF STANDARD DEVIATION σ

Values	Rejections, %
σ	32
2σ	4.6
2.6σ	1.0
3σ	0.27
4σ	0.006

control is shown by a value of $\overline{X}$ as near as possible to X_i and a constant value of σ. This criterion holds for the great majority of practical cases, even though the distribution is appreciably skew or irregular.

The usual quality-control chart consists of quality data plotted chronologically in graphical form, and it is best to insert both action and warning lines, as in Fig. 14, so as to help in securing good control. If the two pairs of lines are calculated in terms of σ, then the probability of an individual exceeding these values is given by Table I, and too high a frequency of points outside the 2σ-band would serve as a warning that the process may be moving out of control. A close watch can then be kept on the process to see whether the departure is a significant one. If it is, action to correct a persistent error can be taken with confidence when the action line is reached, and the amount of rejected product so kept to a minimum. Quality-control charts also show any evidence of drift in a process. This will

be evident from a gradual widening of the difference between the $\bar{X}$ and X_i values, and in magnified form gives the pattern shown in Fig. 15. The re-setting of the process at D is the obvious action to take and, if drift is inherent in the process, appropriate new action and warning lines can be drawn.

Some instances occur in industry where the only satisfactory measure of the quality of a product is its performance in service. Little difficulty is caused by this when the number of items concerned is large, but when the number is small, and when some guidance is urgently needed for control purposes because the consequences of any decision are far-reaching, then operational research methods may be used. The object of operational research is to collect and analyze data obtained during normal manufacturing operations or usage, and to present the results as a basis for executive action. It is best separated from normal research activities, and is usually conducted by a group reporting directly to an executive, who, in this instance, would be responsible for controlling some essential technical factors in production. Statistical methods of analysis are invariably selected for dealing with the collected data, and a few results can be treated as effectively as large numbers. The only consideration when dealing with a few individuals is that the decisions to be made should

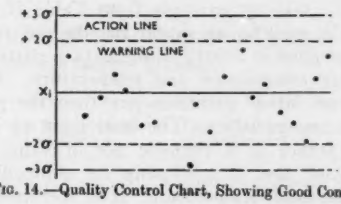


FIG. 14.—Quality Control Chart, Showing Good Control.

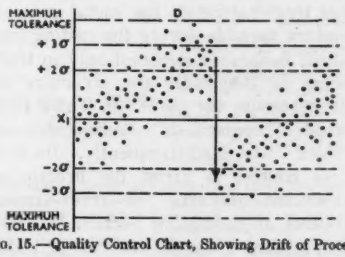


FIG. 15.—Quality Control Chart, Showing Drift of Process.

be of sufficient importance to justify the higher cost of analysis of the data. These were, of course, precisely the reasons prompting the widespread use of operational research during the latter stages of the Second World War. The method has great flexibility and uses all the available data for deciding the action to take at any given time and the standard at which to operate a control. It seeks to obtain the best answer from data that are necessarily limited and inadequate, and as such it should not be ignored.

VIII.—THE TECHNICAL CONTROL OF PROCESS VARIABLES IN INDUSTRIAL PRACTICE

After surveying the principles of control of quality it is instructive to see to what extent they have been applied in practice. A review of all the metallurgical manufacturing processes would be far too lengthy, and it is intended to give here as an example only the melting and casting operations for producing non-ferrous ingots. Table II summarizes the situation, but is intended to be typical rather than comprehensive, although it represents the present state of technical advancement in the foundry. The principal purpose of the table is not so much to show present practice as to bring out ways in which technical advances may be made in the future.

We have already seen that in any manufacturing process there are variables whose control is essential for the output of a high-quality product. When such a variable was fundamental in relation to the process, we termed it primary, and when a variable was introduced only because it affected a primary variable, we termed it secondary.

To take an example from Table II, in the melting operation the desired end-product is a bath of metal of a particular composition and temperature. The two latter quantities are then the primary variables. The heat input to the furnace is a variable not of value in itself and is used only for controlling the bath temperature. It is therefore a secondary variable. On the other hand, the temperature of the metal is a secondary variable during the casting operation, because it is useful only in that it helps to determine the structure and properties of the ingot. In Table II the words "controlled," "adjusted," and "fixed" are used frequently. In every case control is given the precise and restricted meaning of error-actuated control, as defined in Section IV. Control is thus dynamic, and can be clearly distinguished from adjusting or fixing, which are essentially static.

An examination of Table II reveals that the only primary variable always controlled is the temperature of the metal in the melting operation. In view of the remarks made earlier as to the advantages arising from the control of a primary variable, this is a depressing state of affairs. It is true that in some instances other primary variables numbered (2), (5), (6), and (11) are controlled, but this is by no means universal. The reasons for the relative absence of control are, of course, the associated practical problems, which are undoubtedly of considerable magnitude. It is significant that the variables numbered (2) and (5) are quite recent additions, and in particular the rapid analysis of the metal bath is becoming more and more attractive to manufacturers. The practical problems of controlling other primary variables will gradually be solved and bring a corresponding increase in the quality of the product. The control of secondary variables is less necessary when primary variables are controlled, and in any case they present an easier problem. Similar situations occur in other sections of non-ferrous metal manufacture, such as rolling, forging, drawing, annealing, heat-treatment, and welding. The general picture is, in fact, that big opportunities are offered for improving quality by the extension of control to other primary variables in manufacture.

IX.—CONCLUSIONS

(1) Physical measurements of quality characteristics should be made wherever possible in order to control production with certainty at economic tolerances and rejection rates.

(2) It is expected that an extension of automatic control to many metallurgical operations will occur in the near future. A better understanding of all industrial processes involving a human operator will result from applying the principles derived from the study of automatic control mechanisms.

(3) The use of continuous manufacturing processes will increase, together with the application of statistical quality control for achieving high and consistent quality at low cost. A greater use of statistical methods in industrial problems involving small numbers of products may be forecast.

(4) From a sample survey it is concluded that advances in the control of quality will be made by extending technical control to cover more of the primary variables in manufacture.

TABLE II.—THE MEASUREMENT AND CONTROL OF PROCESS VARIABLES DURING THE MELTING AND CASTING OF NON-FERROUS METALS

Operation	Variable	Type	Method of Measurement or Inspection	Type of Adjustment or Control
Melting	(1) Temperature of melt	Primary	Pyrometer or visual estimation	Manually controlled to required temperature by adjustment of fuel or power
	(2) Chemical composition of melt	Primary	Analysis of samples	Usually fixed by heat weighing. Occasionally controlled in accordance with rapid spectrographic analysis. With copper the oxygen content is controlled in accordance with the "set" of cast samples
	(3) Heat input to furnace	Secondary	Metering of fuel or power	Manually adjusted for the control of (1)
	(4) Composition of furnace atmosphere	Secondary	Not generally measured	Rough adjustment made by means of air and fuel supplies, see (5)
Degassing and fluxing of melt	(5) Gas content of melt	Primary	Pfeiffer method, or visual observation of cast samples; density measurements	Sometimes controlled manually by adjustment of degassing agent or furnace atmosphere
	(6) Structural potentialities of melt (aluminum-silicon alloys and magnesium)	Primary	Examination of fracture of cast sample	Sometimes controlled manually by adjustment of sodium, flux, or other additions
	(7) Gas flow (chlorine, nitrogen, &c.)	Secondary	Metering of flow and quantity	Gas flow either fixed or manually adjusted for the control of (5)
	(8) Flux additions	Secondary	Weighing	Flux additions either fixed or adjusted for the control of (5) or (6)
Casting	(9) Structure of ingot	Primary	Visual examination or measurement of grain-size, segregation, structure, and inclusions	No short-term control. Structure determined by (12), (13), (14), and (15)
	(10) Properties of ingot	Primary	Measurement of mechanical properties, density, porosity, hot and cold deformation; examination for internal defects by X-ray or ultrasonic methods	No short-term control. Properties determined by (9), (12), (13), (14), and (15)
	(11) External characteristics of ingot	Primary	Examination for surface defects, piping, and cracks	Partially controlled by adjustment of temperature and rate of pouring
	(12) Rate of pouring	Secondary	Visual estimation or fixed by tundish	Adjusted for control of (11) within certain limits fixed by (9) and (10)
	(13) Temperature of pouring	Secondary	Pyrometer or visual estimation	Usually fixed; occasionally adjusted for control of (11) within certain limits fixed by (9) and (10)
	(14) Mould temperature	Secondary	Pyrometer or unaided judgment	Fixed
	(15) Rate of withdrawal of ingot and flow of water in continuous-casting process	Secondary	Metering of withdrawal rate and flow of water	Adjusted for control of (11)

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SOME USES OF INTERINDUSTRY STATISTICAL TECHNIQUES

H. BURKE HORTON

THE AUTHOR

majored in statistics at the University of Texas completing his BBA in 1937 and MBA in 1938. He taught statistics and accounting for two years. Further graduate work at Columbia University was interrupted by World War II. After one year as a civilian statistician in Washington, D. C., he was commissioned and trained as a Naval Aerologist. His service in the Pacific Theatre included a final assignment as Aerologist, Com Phib Group 12, under (then) Rear Admiral John L. Hall. Since the war he has been a statistician with the Interstate Commerce Commission, and is now Chief of the Interindustry Research Office, Hq. USAF.

Note: This article is a revision of a presentation which was made at the St. Louis session of the National Academy of Economics and Political Science on 29 December 1952.

The interest of the Department of Defense in improved methods for testing the feasibility of its programs has grown steadily during World War II and subsequent years. The old-style adamant insistence on military "requirements" which must be met at all costs has given way at all echelons to a healthy respect for the limitations imposed by the nation's industrial and natural resources. This increased emphasis upon consideration of the nation's capabilities is, in large measure, the result of the too frequent adjustment, readjustment, and hasty alteration of plans which occurred during the period 1942-1945.

To a great extent past difficulties have been due to inadequate means of measuring and taking account of the goods and services needed *indirectly* in the course of carrying out a war plan. Examples of such indirect requirements are motors and generators for installation in airframes; steel castings for tank hulls; and electric cable for use in submarine construction. These in turn generate further indirect requirements such as ball bearings for electric motors; coal and ores for basic metal industries; and transportation services and electric power needed in all of these production processes. The greatest single advantage of the Interindustry Tech-

nique is that it provides a systematic framework for taking account of all requirements, direct and indirect.

Attempts were made during World War II to carry out production programs which were infeasible from the outset. Expediters of particular parts of the overall program competed with one another for scarce materials, components, and manpower. The resulting confusion led to substantial increases in the size of governmental agencies charged with responsibility for meeting production schedules. To alter delivery schedule frequently enough to reflect unforeseen scarcities, governmental control of production processes was extended beyond the point originally considered to be necessary. The restrictions thereby placed on industrial management sometimes tended to stifle initiative, lower plant efficiency, and increase costs.

A large part of these costly difficulties was the direct result of attempting to carry out an initially infeasible program. In effect, the nation's productive apparatus was used as a gigantic analog computed to test ex post facto, the feasibility of a whole series of programs. The answers showed up in the form of insuperable production difficulties, time delays, and constantly changing delivery schedules, rather than as red lights on a control panel. Such a "computation" by trial and error could easily cost the nation more time than it can spare in the event of a new emergency.

Our present objective is to remove at least a part of this trial-and-error process from the nation's industrial establishments and to place it instead in the computation laboratory. Modern computing equipment has made this a practical objective. However, there are a number of extremely difficult stages between the nation's industrial activities and the computation laboratory. We are no closer to "pushbutton" programming than we are to "pushbutton" warfare. We have completed the broadest outlines of a procedure for representing the nation's industries by means of systems of equations. Modern electronic computers, specifically the SEAC (1), and the UNIVAC (2), have demonstrated that they can handle the simplified mathematical structures which can be based upon data now available. These structures are very coarse approximations to the nation's intricate productive system. Their validity depends upon the persistence of past production techniques and our ability to foresee and incorporate in our structures the more important departures from past interindustry relationships.

The cooperation of industrial management is needed to improve the quality of our basic data. We would like to see our computational structures perfected so that grossly infeasible plans will be modified prior to initiation. If this can be done, the production processes will run more smoothly, greater reliance can be placed upon decentralized operational control by private management, and the governmental control apparatus can be streamlined and held down to the very minimum necessary under mobilization conditions. Plant managers are familiar with the principle that sound advance production planning, based upon reliable data furnished by departmental supervisors, results in less frequent later interference in the affairs of each department. Similarly, the procedures which we are now attempting to perfect are advance planning tools—not operational control devices.

The mathematical structures or "models" which we are now using are the result of a marriage of linear programming techniques, as applied to internal Air Force activities (3), and the "input-output" or interindustry techniques of economic analysis originally developed by Professor Wassily Leontief, Harvard University (4), and developed further by staff members of the Bureau of Labor Statistics, U. S. Department of Labor (5).

The principal ingredient in such a

mathematical model is a set of functions which express in quantitative terms the relationship between each industry's output and its requirements for the products of other industries on current account. I emphasize at this point the phrase "current account." Our analytical procedures handle in separrate and distinct stages current account purchases needed to support production without increase in capacity, and capital account purchases required to increase capacity.

The Division of Interindustry Economics, Bureau of Labor Statistics, U. S. Department of Labor was given the task of assembling the first postwar interindustry transactions table. This table was based upon the 1947 Census of Manufactures, the 1948 Census of Business and a variety of supplementary sources. The basic study was carried out in 450 industry detail, with supporting product analyses for many industries. The Standard Industrial Classification, by which each plant is assigned to an industrial class according to its principal product, was adopted as our basic classification. The heterogeneity of the output of many industrial sectors and the lack of acceptable physical measures of output in such instances led to the adoption of dollar sales (or purchases) as the principal unit of output (or consumption).

For computation purposes the 450 industry table was condensed to 190 industrial sectors. Table 1 is an extract from this condensed table. It shows, for example, that the Motor Vehicle Industry purchased $36.4 million of Electric Power in 1947. The Electric Power Industry in turn purchased $7.5 million of Motor Vehicle products in 1947; this was in addition to capital outlays for complete new vehicles.

The limited amount of information now available for any one cell of this table precludes the use of elaborate functions relating consumption to output. If we assume that inputs or purchases for current account are proportional to outputs, a set of coefficients can be obtained (See Table 2). This table shows, for example, that if sales and purchases (measured at 1947 price levels) vary proportionately, $76,986 of electric power is required to produce $1,000,000 of primary aluminum (6). The network of industrial interrelationships is so complex that the output required of any given industry can be determined only by summing an infinite set of values. It can be shown that this sum is finite.

If we denote by A the matrix of coefficients from which Table 2 is extracted, the "inverse complement of A," or symbolically, $(I-A)^{-1}$ is a matrix of factors which makes possible the direct calculation of such sums. Table 3 is an extract from the 190 order inverse complement of A (7). Granting the basic assumptions, Table 3 shows that consumer's orders for $1,000,000 of motor vehicles generates the following outputs by other industries: Railroads, $52,376; Electric Light and Power, $15,867; Coal Mining, $15,515; and so on, as shown in column 145.

The total of column 145 in the complete table is approximately $2.7 million. This means that $1.0 million of motor vehicles produced for final consumers generates *indirect* effects of $1.7 million as measured in terms of plant sales for all industries. Thus, a total of $2.7 million of transactions is required to fill an order for $1.0 million of motor vehicles.

Reading across row 169, (Railroads) of Table 3, we obtain the gross output of rail transportation service required to support the final consumption of $1,000,000 of each product listed at the top of the table. This type of table should be of interest in market analysis, although it was not developed for this purpose. The row for each industry contains a set of factors which measure the given industry's stake in the consumption of products of all other industries. For example, the Ball and Roller Bear-

TABLE 1

EXTRACT FROM TABLE I, INTERINDUSTRY FLOW OF GOODS AND SERVICES BY INDUSTRY OF ORIGIN AND DESTINATION (1)

CONTINENTAL UNITED STATES, 1947

(millions of dollars)

Sector No.	Industrial Sector	4	16	49	58	88	127	145	148	167	169	All Other Industries	Final Demand (2)	Gross Domestic Output
4	Food Grains and Feed Crops	817	0	25	0	0	0	0	0	0	0	10,100	62	11,004
16	Coal Mining	0	15	17	(3)	(3)	(3)	15	1	385	408	1,751	444	3,036
49	Industrial Organic Chemicals	5	0	264	3	0	0	9	0	1	(3)	1,179	211	1,672
58	Fertilizers	246	0	1	61	0	0	0	0	(3)	0	197	18	523
88	Primary Aluminum	0	0	0	0	0	0	0	0	0	0	301	—16 (4)	285
127	Ball and Roller Bearings	0	0	0	0	0	17	105	6	0	2	213	44	387
145	Motor Vehicles	58	15	0	0	0	0	3294	22	8	(3)	1,738	7,385	12,520
148	Aircraft	0	0	0	0	0	0	17	143	0	0	81	1,364	1,605
167	Electric Light and Power	6	56	19	3	22	4	36	10	396	28	3,562	295	4,437
169	Railroads	117	6	41	47	4	4	237	12	128	412	4,262	4,689	9,959

(1) Each row shows distribution of output of producing industry named at left. Each Column shows input distribution for purchasing industry named at top.

(2) Final Demand is the consolidation of Households, Inventory Change, Gross Private Capital Formation, Government, Foreign Trade, Construction, Stockpile, Waste Products, Small arms, and Small arms ammunition.

(3) Less than $500 thousand.

(4) Very little primary aluminum enters into Final Demand. Most of the output is used as an intermediate product. A decrease in inventory in 1947 and some imports (negative Final Demand) account for the minus sign.

SOURCE: U.S. Department of Labor, Bureau of Labor Statistics, Division of Interindustry Economics, October 1952.

TABLE 2

EXTRACT FROM TABLE II, DIRECT PURCHASES PER MILLION DOLLARS OF OUTPUT (2)
CONTINENTAL UNITED STATES, 1947

Sector No.	Industrial Sector	4	16	49	58	88	127	145	148	167	169
4	Food Grains and Feed Crops	74,216	0	15,143	0	0	0	0	0	0	0
16	Coal Mining	0	4,821	10,268	430	994	977	1,190	581	86,684	40,978
49	Industrial Organic Chemicals	421	0	158,725	5,116	0	0	715	0	284	5
58	Fertilizers	22,329	0	608	116,187	0	0	0	0	6	0
88	Primary Aluminum	0	0	0	0	0	0	0	0	0	0
127	Ball and Roller Bearings	0	0	0	0	0	54,896	8,371	3,707	0	150
145	Motor Vehicles	5,300	4,997	0	0	0	0	268,605	13,848	1,682	24
148	Aircraft	0	0	0	0	0	0	1,331	91,473	0	0
167	Electric Light and Power	499	18,319	11,163	6,298	76,986	9,284	2,906	6,329	89,140	2,845
169	Railroads	10,638	1,961	24,449	89,348	13,728	9,473	18,946	7,199	28,758	41,321

(1) Each entry shows direct purchase from industry named at left by industry at top per million dollars of output of the latter.
SOURCE: U.S. Department of Labor, Bureau of Labor Statistics, Division of Interindustry Economics, October 1952.

TABLE 3

EXTRACT FROM TABLE III (TRANSPOSED) DIRECT AND INDIRECT REQUIREMENTS PER MILLION DOLLARS OF FINAL DEMAND (1)

CONTINENTAL UNITED STATES, 1947

UNIT: $1,000

Sector No.	Industrial Sector	4	16	49	58	88	127	145	148	167	169
4	Food Grains and Feed Crops	1,086.5	.5	27.3	5.0	1.2	.5	2.7	.8	.3	1.6
16	Coal Mining	7.2	1,009.0	36.2	39.2	25.2	11.8	15.5	7.5	99.0	45.4
49	Industrial Organic Chemicals	3.5	1.9	1,212.3	32.2	22.9	1.8	12.4	3.6	1.4	1.5
58	Fertilizers	28.0	.1	3.5	1,135.7	4.0	.1	.4	.2	(2)	.1
88	Primary Aluminum	.1	.6	.7	.7	1,026.1	1.7	4.7	11.4	.1	.7
127	Ball and Roller Bearings	.5	.6	.3	.3	2.2	1,058.9	14.1	5.6	.2	.4
145	Motor Vehicles	13.7	9.0	3.1	3.3	4.2	1.4	1,376.2	23.9	4.3	2.3
148	Aircraft	.1	.1	.1	.1	.1	.1	2.3	1,100.9	(2)	.2
167	Electric Light and Power	11.7	22.7	23.1	20.7	100.5	16.8	15.9	14.7	1,101.6	6.3
169	Railroads	21.3	7.7	54.3	136.0	55.0	25.9	52.4	21.1	36.0	1,047.3

(1) Each entry shows, per million dollars of deliveries to final demand by industry named at top, total dollar purchases directly and indirectly required from industry named at left.

(2) Less than $50.

SOURCE: U.S. Department of Labor, Bureau of Labor Statistics, Division of Interindustry Economics, October 1952.

TABLE 4

INPUT LEAD TIMES FOR SELECTED INDUSTRIES (1)

UNIT: 1 quarter

Sector No.	Industry	4	16	49	58	88	127	145	148	167	169
4	Food Grains and Feed Crops	4.0	—	0.7	—	—	—	—	—	—	—
16	Coal Mining	—	0.7	0.7	0.7	0.5	1.5	0.9	1.3	1.0	0.5
49	Industrial Organic Chemicals	4.0	—	0.7	0.7	—	—	0.9	1.3	1.0	2.1
58	Fertilizers	4.0	—	0.7	0.7	—	—	—	—	1.0	—
88	Primary Aluminum	—	—	—	—	—	—	—	1.3	—	—
127	Ball and Roller Bearings	—	—	—	—	—	1.5	0.9	1.3	—	2.1
145	Motor Vehicles	4.0	0.7	—	—	—	—	0.9	1.3	1.0	2.1
148	Aircraft and Parts	—	—	—	—	—	—	0.9	1.3	—	—
167	Electric Light and Power	1.9	0.3	0.2	0.2	0.1	0.6	0.3	0.6	0.1	0.1
169	Railroads	3.8	0.6	0.6	0.6	0.4	1.4	0.9	1.3	0.9	1.1

(1) Each entry shows the average time by which the delivery of goods and services of the industry listed at the left must precede the delivery of completed products of the industry listed at the top.

SOURCE: U.S. Department of Commerce, Office of Business Economics, Business Structure Division.

ing industry has a stake of $14,100 in an order for $1,000,000 of motor vehicles.

Thus far, no mention has been made of the time phasing of production. Timing is of the essence in mobilization planning. Table 4 is extracted from a 190 order table prepared from data furnished by the Office of Business Economics, U. S. Department of Commerce. Each factor measures in quarters the average time interval by which goods and services from the industry at the left must precede the output of the industries listed across the top. These factors were estimated primarily from inventory data (reciprocal of turnover rates) with certain additional adjustments. Looking at row 127, column 145, Table 4, we find that ball and roller bearings should be delivered to plants of the Motor Vehicle industry an average of 0.9 quarter prior to delivery of a completed automobile or truck. For computation purposes integral lead times are desirable; so the associated input coefficient is split in the ratio of 9 to 1. The first portion is assigned an input lead time of 1.0 quarter and the second portion receives a lead time of 0.0 quarter, thereby preserving the average lead time of 0.9 quarter.

The use of integral lead times changes a time-phased model to the same form as a very large static model. If there are 190 industries and 16 time periods (4 years, by quarters) plus a 17th period for "level off" (8), then there are 17 x 190 or 3230 variables to be computed. This can be handled in the same manner as a 3230 x 3230 static problem. However, by taking advantage of certain special characteristics of the system, it is possible to reduce this unmanageable system to seventeen 190 x 190 systems solved in sequence (9).

Our first large computation, called the "Emergency Model," has been completed and the results are being appraised. It was based upon 1947 coefficients brought up to date as of about 1951 in important areas. In addition, it was necessary to supplement the listed industries by special analyses of important military end items not in production in 1947. The design of sampling procedures to determine the industrial impact of the host of civilian-type items procured by the three services is also a complex task. This type of work occupies the time of a considerable portion of the staff of the Air Force Interindustry Research Office.

Before this structure and the computed military requirements could be used, estimates of non-military final demand were needed to round out the complete picture of requirements. These estimates were prepared by governmental agencies outside the Department of Defense. The many problems involved in these areas lie outside the scope of this brief paper.

Analytical tools of the type described above have been developed as part of the Air Force research program in interindustry economics. This program was undertaken at the request of the Department of Defense. Army and Navy personnel are assisting in translating military requirements into the precise form necessary for these mathematical structures. In addition to the projects mentioned above, techniques are being developed for the purpose of translating production schedules into manpower requirements, industry by industry. Other projects, which are well underway, will provide a means for quickly determining the effect of adding new capacity in industries found to be deficient in the course of a computation. The Bureau of the Budget has accepted the task of monitoring the research projects carried on by other governmental agencies and universities.

If, as a result of this research, any major differences between our military requirements and our industrial capabilities are brought to light, the program will have been worthwhile. Corrective action may be taken on both sides of such discrepancies. If urgent military necessities do exceed present or

prospective capabilities, it is highly important that this be known years in advance, while there is time to take corrective action. If the indicated corrective action itself exceeds our means, then there is a need to review the military necessities. Early review will guard against the haphazard, unbalanced readjustments which will surely occur if an infeasible program it attempted and the cutbacks made in haste. It appears to us that a substantial portion of these major difficulties can be brought to light by present interindustry analytical procedures. It is highly desirable that this process of review and adjustment take place in the computation laboratory in advance of an emergency, rather than in the nation's factories, when it is too late for expansion of industrial capacities or for balanced program changes.

References

1. Standard's Eastern Automatic Computer, National Bureau of Standards, Washington, D. C.

2. UNIVersal Automatic Computer, produced by the Eckert Mauchly Division of the Remington Rand Corporation. UNIVAC No. 2 was accepted by the Air Force on June 25, 1952, and is now operating in the Pentagon 24 hours per day, 7 days per week. The Mathematical Computation Branch of the Planning Research Division is responsible for its operation.

3. See, for example, "Programming of Interdependent Activities, I General Discussion" by Marshall K. Wood and George B. Dantzig, Econometrica, Vol. 17, pp. 193-199, and (same title) "II Mathematical Model" by George B. Dantzig, Econometrica, Vol. 17, pp. 200-211.

4. "The Structure of the American Economy, 1919-1929," New York, 1941. Now available in revised form, "The Structure of the American Economy, 1919-1939," New York, 1951.

5. See, for example, "The Interindustry Relations Study for 1947" by W. Duane Evans and Marvin Hoffenberg, *The Review of Economics and Statistics,* May, 1952.

6. Non-homogeneous linear form (i.e., linear non-proportional relationships) can be handled with ease by present computing equipment. Such linear relationships can frequently be used over a wide range of values to give a satisfactory approximation to a more complicated function. However, insufficient data are available in most cases to serve as a basis for altering the assumed proportional relationship.

7. The inversion of this 190 order matrix was one of the largest integrated mathematical operations ever to be successfully completed. It involved about 7,000,000 accurate multiplications of 9-digit numbers. This job was done in less than 50 hours. Air Force and Eckert-Mauchly personnel worked jointly to complete the operation, using the Bureau of the Census' UNIVAC No. 1 in Philadelphia. A number of such large-scale inversions have since been performed on the Air Force UNIVAC in the Pentagon.

8. This permits the assumption of continuing production at constant levels for all industries in the post-model years.

9. The procedure, suggested by Dr. George Suzuki of the Air Force interindustry Research Office, takes advantage of the fact that indirect effects either precede or occur in the same time period with outputs. Consequently, if the last time period is solved first, indirect requirements from subsequent time periods can be determined. The computation proceeds backwards in time, yielding a set of solutions for each time period. The problem was handled by an iterative procedure on the SEAC.

APPARATUS AND PROCEDURES FOR PREDICTING VENTILATION SYSTEM NOISE

ACKNOWLEDGMENT

This paper, describing a method of measuring the acoustic power output in watts and the frequency spectra of ventilating fans operating into ducts, was published in the March 1953 edition (Volume 25, No. 2) of "The Journal of the Acoustical Society of America." Its authors were MR. L. L. BERANEK, Lieutenant J. L. REYNOLDS, USN, and Lieutenant (junior grade) K. E. WILSON, USN. The work on which this paper was based was accomplished at the Acoustics Laboratory, Massachusetts Institute of Technology, while Lieutenants Reynolds and Wilson were engaged in postgraduate study.

I. INTRODUCTION

The ventilation design engineer has long been handicapped by his inability to predict quantitatively, prior to its installation and operation, the acoustical performance of a ventilation system. This difficulty is largely due to the lack of adequate knowledge of the acoustical characteristics of the various elements comprising the overall system. Design engineers are becoming more aware of ventilating noises, but at present the standard acoustic tests as carried out by fan manufacturers[1] involve only overall sound pressure level measurements around the outside casing of the fan. These tests are seldom conducted in free-field surroundings and give no information on the frequency spectrum of that fan.

This paper presents a method for determining the exhaust and intake frequency-spectra of ventilating fans and gives procedures for using this information in predicting the performance of ventilating systems for rooms. The results of measurements made on five fans are presented in a companion paper.[2]

II. SOUND POWER LEVEL

The sound power level produced by a source of noise in a particular frequency band is logarithmically related to the sound power in watts produced by the source of noise in that band. By definition, the power level PWL in decibels is:—

$$\text{PWL} = 10 \log_{10} \left(\frac{W}{10^{-13}} \right) \text{db re } 10^{-13} \text{ watt} \qquad (1)$$

where W equals the acoustic power in watts. For example, if W = 1, PWL = 130 db. For each factor in power of 10 more or less, add or subtract 10 decibels. For example, if W = 100 watts, PWL = 150 db, and if W = 0.01 watt, PWL = 110 db.

The *total power level* is calculated from the total power in all bands.

The systems that we describe below for measuring fan noise are designed to determine the power levels in frequency bands and the total power level.

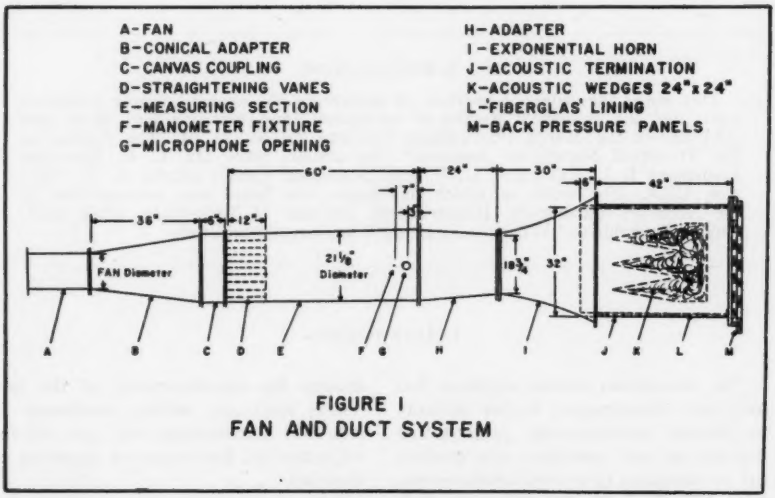


FIGURE I
FAN AND DUCT SYSTEM

III. System for Measuring the Noise Produced by a Fan in Ducts

A. Initial System

General description—The measuring system initially developed for determining fan noise is shown in Fig. 1. The main components are the fan, a measuring duct and an anechoic termination.[3] If needed, the fan is coupled to the measuring section by a conical adapter. A heavy canvas coupling is used to prevent the structure-borne vibrations of the fan from entering the measuring section and giving false readings.

In the initial system, the microphone was placed at the center of the duct at a point about 8 feet from the fan. Since a U. S. Navy type A3 fan was the largest fan available for the tests, the inside of the duct was made to correspond to its 21⅛ inch diameter. The measuring duct was 5 feet in length, of circular cross-section, and constructed of 1/16 inch galvanized steel coated with a ¼ inch-thick layer of vibration damp-

ing mastic. Conical adapter sections, 3 feet in length, were also constructed to adapt other fans to the measuring duct. Nine straightening vanes were inserted in the duct about 4 feet from the fan in order to reduce the turbulence of air flow. A manometer connection and microphone opening were placed at the top of the measuring duct as shown in Fig. 1.

An exponential horn, square in cross-section for ease of construction and made of ¼ inch plywood, coupled the measuring duct to the anechoic termination. The square section of the horn made it necessary to insert a circular-to-square cross-sectional steel adapter between it and the measuring duct. Fitted to the large end of the horn was an anechoic termination. This consisted of a large square duct lined with a one-inch thickness of 6 lb/ft^3 Fiberglas. In its center were suspended three 8 x 24 inch Fiberglas wedges, leaving an open space around the edges equal to the cross-sectional area of the duct. Incorporated in this termination was a method for quickly varying back pressure. This was accomplished by covering the end with two contiguous perforated panels. The open area of these perforations was also equal to the cross-sectional area of the measuring duct. By sliding the outer panel with respect to the inner fixed panel, any desired area could be left open so as to determine the back pressure.

Instrumentation—Basically, the instrumentation for measuring the fan noise consisted of a microphone, a windscreen and an indicating device. An Altec-Lansing, model 21-B condenser microphone was used because of its small physical size and its relatively flat response over the desired frequency range. It was fitted with a windscreen to eliminate as much as possible the generation of noise by the airstream. (See Fig. 2.) The output signal was amplified by an Altec-Lansing line amplifier and measured on a Ballantine electronic voltmeter.

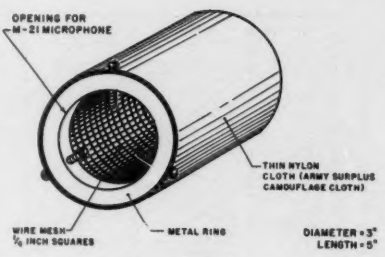

OPENING FOR M-21 MICROPHONE
THIN NYLON CLOTH (ARMY SURPLUS CAMOUFLAGE CLOTH)
WIRE MESH ⅛ INCH SQUARES
METAL RING
DIAMETER = 3"
LENGTH = 5"

Figure 2

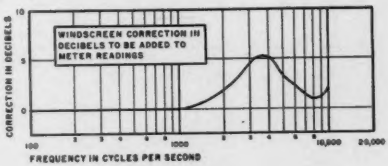


Figure 3

The microphone was calibrated to read absolute sound pressure level relative to 0.0002 microbar. This reference level was used throughout the work. The windscreen was calibrated and the small corrections shown in Fig. 3 were found necessary at the higher frequencies. The self-noise characteristics of this screen were measured at two wind speeds as a function of frequency and are shown in Fig. 4.[4]

In order to determine the noise levels in different frequency bands, one-third octave band filters were introduced in the system before the electronic voltmeter. Although that type of filter set is not used in the United States as widely as octave band filter sets, the larger number of frequency bands provides valuable information. Conversion from one-third octave to octave band readings is relatively easy. The filter set was calibrated and an average correction number for each band was established.

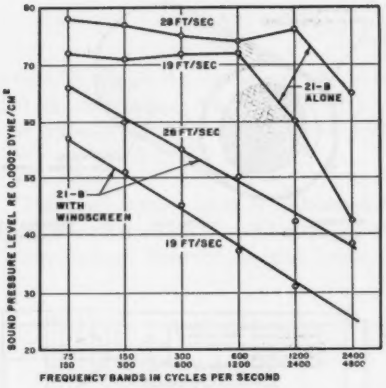


Figure 4

Back pressures to the fans were measured directly by an Ellison inclined draft gauge, giving pressures in inches of water. Speed control of the d-c current fan motors was obtained by varying armature current and, when necessary, field excitation.

Vibration isolation—The canvas vibration break was found to be very necessary. Comparison of curves measured with and without it showed differences of as much as 10 db in some of the frequency bands. In well-designed ventilation systems, canvas breaks are commonly employed so that the use of them in the experimental setup is believed desirable.

Longitudinal standing waves — The effectiveness of the anechoic termination was determined by measuring sound pressure levels along the axis in the horn itself and in the test section preceding it. Variations in levels of the order of ± 1.5 db with position were found between 100 and 5000 cps. These variations included, however, not only reflections from the termination, but also non-uniformities in the sound field arising from the size and constructional details of the duct itself.

Tranverse standing waves—The microphone was moved transversely across the duct in order to determine the effects of the radial modes of vibration in the tube. It was expected that lateral resonances would produce the principal inaccuracies in the measuring set-up. The data from one of those tests are plotted as a function of frequency in Fig. 5.

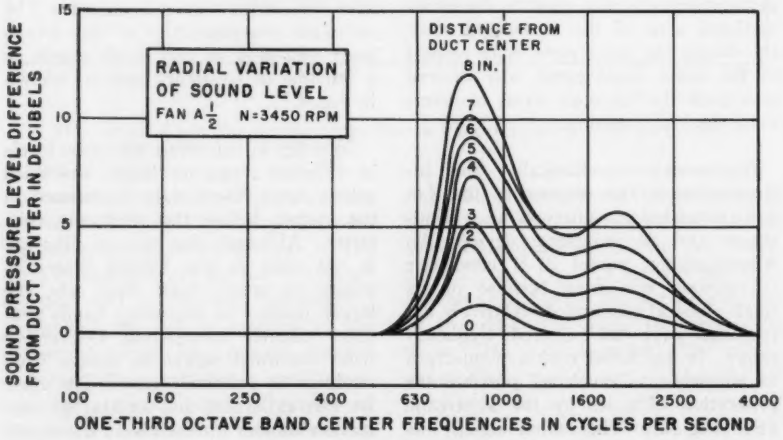


Figure 5

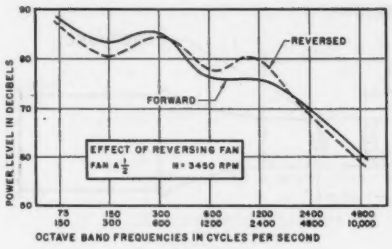


Figure 6

It is seen that the principal resonances occurred at about 800 cps and at about double that frequency. The indicated differences of up to 10 db show that between 600 cps and 3000 cps errors will probably be introduced into the power level data amounting to as much as 5 db if a single microphone position is used. From a fan design engineer's standpoint this amount of error may be of some concern. However, inspection of the smooth curves obtained on a number of fans reveals that for practical application of the results in ventilation system design, the accuracy is adequate. A position at the center of the duct was ultimately chosen because the results obtained there correlated most closely with the total power delivered to the anechoic termination. Basic research into the reaction of these duct resonances on the total sound power is also indicated.

Effect of reversing fan—The change in power level spectrum produced by reversing the fan so that it sucked rather than blew air was studied for one fan. The results are shown in Fig. 6. It is seen that the reversal produced only a small change in the amount of noise.

Determination of power level—The power level in any frequency band was determined by first measuring the sound pressure level in decibels in that band at the center of the duct. The SPL is defined as follows:—

$$\text{SPL} = 20 \log_{10}\left(\frac{\text{p}}{0.0002}\right) \text{ db } \underline{\text{re}}\ 0.0002 \text{ microbar} \qquad (2)$$

where p is the sound pressure in dynes/cm² (microbars). If the sound intensity is uniform across the duct, the sound pressure level in the duct is related to the power level by the equation,

$$\text{PWL} = \text{SPL} + 10 \log_{10} \text{S} - 0.5 + 10 \log_{10}\left[\sqrt{\frac{\text{K}}{293}}\left(\frac{30}{\text{B}}\right)\right] \text{ db } \underline{\text{re}}\ 10^{-13} \text{ watt} \qquad (3)$$

where,

S = cross-sectional area of the measuring section of the duct in square feet,

K = absolute temperature of the air in degrees Kelvin, and

B = total barometric pressure in inches of mercury.

To the degree of accuracy usually necessary in ventilating system design, this formula can be approximated by

$$\text{PWL} \doteq \text{SPL} + 10 \log_{10} \text{S}. \qquad (4)$$

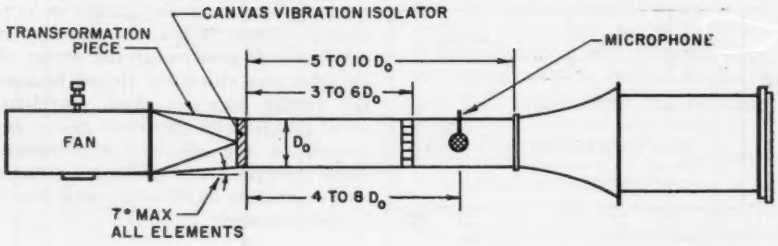


Figure 7

B. Recommended System

General description—It is recommended that future systems for measuring the noise characteristics of ventilating fans should be constructed more nearly like those described by the NAFM[1] for measuring fan performance (air volume, pressures, efficiencies, etc. at a stated density). In their Bulletin No. 110, they give duct and air straightener designs for 8 types of fans.

In brief, we believe that the fan is ideally connected to a circular section of duct about equal in diameter to the fan diameter and five to ten diameters in length. (See Fig. 7.) Three to six diameters from the input end of this duct an air straightener is located. The acoustic measurements are made with a condenser microphone enclosed in a windscreen located four to eight diameters from the input end. Measurements of temperature and barometric pressure should be made at all times. It is also believed that further studies should be undertaken on the best position of the microphone in the duct, as the data reported in Fig. 5 were taken for one fan only.

Instrumentation—The electronic measuring system should be similar to that used previously, except that in the U. S. A. an eight-band octave filter set can more readily be procured.

A superior type of windscreen, from the standpoint of low self-generated noise (due to the windstream) is believed to be spherical in shape with as large a diameter as is feasible in the duct being employed. The very thin nylon or silk cloth covering for the sphere can be stretched over a metal screen with 0.5 inch mesh squares. A particular calibration should be made to determine the effect of the windscreen on the frequency response of the microphone.

IV. Measurement of Noise in Free Space

Some fans do not couple to ducts. Even those that do often have one side or opening free. Measurements of the power levels produced by a free fan are accomplished by measuring the sound pressure levels in the different frequency bands at a number of positions on a spherical surface around the fan at a distance not less than four times the diameter of the fan.

The acoustic power is obtained from the formula

$$W = (I_1S_1 + I_2S_2 + I_3S_3 + \ldots I_nS_n + \ldots)\ 10^{-7} \qquad (5)$$

where,

W = acoustic power in watts

$I_n = p_n^2/\rho_0 c$ = sound intensity in ergs/cm²/sec as measured at the nth position with a microphone.

$\rho_0 c$ = characteristic impedance of air = 42.86 $(273/°K)^{1/2}(B/30)$ rayls

p_n = sound pressure in dynes/cm² measured at point n

S_n = area in cm² of the spherical surface for which the sound pressure equals p_n

If the radiation pattern has an axis of symmetry, as is usually the case, measurements may be made at a number of points in a plane as shown in Fig. 8. In this case, the total acoustic power radiated is found from,

$$W = \left(\frac{2\pi r^2}{\rho_0 c}\right) \sum_{n=1}^{N} p^2(\theta_n) \sin \theta_n \left(\frac{\Delta\theta}{57.3}\right) \times 10^{-7} \text{ watts} \qquad (6)$$

W = acoustic power in watts in a particular frequency band

r = distance from center of fan in centimeters

$p(\theta_n)$ = sound pressure measured at a point n in dynes/cm².

$\rho_0 c$ = See definition above

$N = 180°/\Delta\theta$ = number of measurements that were made in passing from a point directly in front of the source to one directly behind the source (0 to 180°). For this example, $N = 6$.

$\Delta\theta$ = separation in degrees of the successive points around the sound source at which measurement of $p(\theta_n)$ were made. (See Fig. 8.)

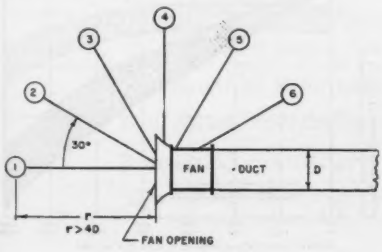


Figure 8

Usually a directivity pattern is plotted. A directivity pattern is the sound pressure level in decibels plotted on polar graph paper as a function of the angle θ_n. The sound pressure p_n is found from the measured sound pressure level with the aid of Eq. (2).

V. Acoustical Design of Ventilating Systems

The acoustical design of ventilating systems for rooms can be broken into five parts:—

(a) Source characteristics
(b) Ducting characteristics
(c) Grille characteristics
(d) Room characteristics
(e) Criteria for permissible sound levels.

A principal concern of this paper has been to describe a method for determining the noise characteristics of the source. In the companion paper,[2] data are presented on several specific fans and on typical unlined ducts with and without bends. The characteristics of lined ducts, lined bends, and grilles have been described previously in summary form in the Heating Ventilating Air Conditioning Guide[5] which should be required reading for ventilation design engineers. Some summary data from one of the author's files are presented here for convenience.

Let us now treat source and room characteristics and the criteria for permissible sound levels. Then we shall give an example of ventilation system design.

A. *Source Characteristics*

The noise characteristics of several vaneaxial and centrifugal fans were given in the accompanying paper[2] in terms of power levels in one-third octave bands plotted as a function of the mean frequencies of the bands. Usually, however, acoustic measurements of sound pressure levels are made in octave bands. One-third octave band levels may be converted to octave bands by adding the powers contained in the three bands within an octave and converting to decibels again.

To assist in the summation of band levels, the chart of Fig. 9 is given. It

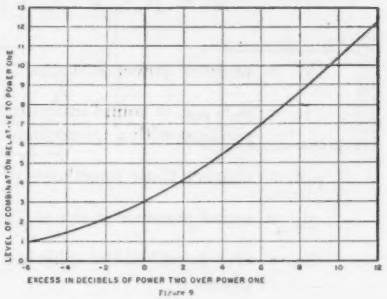
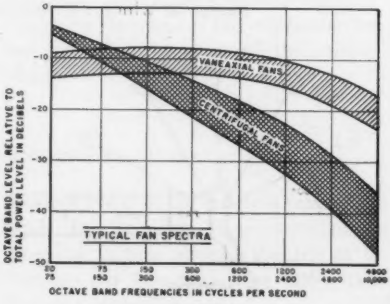


Figure 9

permits easy determination of the level that would be obtained by a single band equal in width to two contiguous bands for which the levels are known. For example, suppose that the octave band level between 300 and 600 cps is desired when the one-third octave band levels are as follows: 80 db in the 284-360 cps band; 79 db in the 360-456 cps band; and 78 db in the 456-568 cps band. Using the chart, we find that the combination of the first two bands gives a level of 82.6 db. The combination of this level with the third band level gives a level of 83.9 db. The final level is that which would be measured by a filter with frequencies between 284 and 568 cps and is approximately equal to the desired level for a 300 to 600 cps octave band.


VANEAXIAL FANS
CENTRIFUGAL FANS
TYPICAL FAN SPECTRA
OCTAVE BAND LEVEL RELATIVE TO TOTAL POWER LEVEL IN DECIBELS
OCTAVE BAND FREQUENCIES IN CYCLES PER SECOND
Figure 10

When the exact acoustic data on a fan are not available, Eq. (7) below and Fig. 10 may be used to yield estimated octave band levels for ventilator fan power levels. Eq. (7) gives the total power level for all bands in decibels. Fig. 10 gives the power levels in octave bands relative to the total power level.

Total Power Level (all bands) =

$$120.4 + 17.7 \log_{10} (HP/N) + 15 \log_{10} (N/6) \text{ db re } 10^{-13} \text{ watt} \qquad (7)$$

where

HP = total horsepower delivered to the fan rotor by the motor

N = number of fan blades

B. *Room Characteristics*

In Fig. 11 we show, arbitrarily, four methods for terminating a ventilating duct in a room. These methods were chosen to correspond to four distinct acoustical situations. Other duct arrangements may be analyzed by interpolation among the four cases shown here.

In each of these cases, the noise power radiated into the room produces sound waves that are reflected from the walls many times to produce reverberant sound. Low frequency sounds radiate from the end of the duct equally in all directions. High frequency sounds are "beamed" in the direction the duct opening is facing. This beaming effect is described mathematically by the directivity factor Q.

The directivity factor Q is defined as the ratio of (a) the intensity produced in a stated direction at a given distance r from a source of sound to (b) the intensity produced at the same distance by a non-directional source located in free space and radiating the same acoustic power. As an example, the directivity factor at low frequencies for a sound source located at the corner (See D of Fig. 11) of a room is equal to 8 because the source radiates the acoustic power into only one quadrant of spherical space. Hence, 8 times as much power goes into the quadrant as would be the case if there were no corner.

The sound pressure level in the room at a distance r from the duct opening, as measured by a sound level meter using the "C" or "flat" network, is given approximately by the formula:—

$$SPL \doteq PWL + 10 \log_{10} \left[\frac{Q}{4\pi r^2} + \frac{4}{R} \right] \qquad (8)$$

where,

PWL = power level of the source in a particular frequency band in db re 10^{-13} watt

Q = directivity factor (dimensionless)

r = distance from the duct opening in feet

$R = \bar{\alpha} S/(1 - \bar{\alpha})$ = room constant in square feet

$\bar{\alpha}$ = average absorption coefficient for the room at the mid-frequency of the band of noise being considered (dimensionless)

S = area of the bounding surfaces of the room in square feet

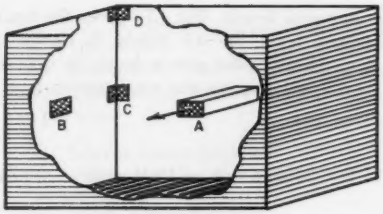


Figure 11

A chart giving the room constant R as a function of the volumes of rooms of live, medium live, medium, and dead types is shown in Fig. 12. The values of $\bar{\alpha}$ for live rooms is assumed to be 0.05; for medium live rooms 0.15; for medium dead rooms 0.25; and for dead rooms 0.4. The relation between the surface area S and the volume V is assumed to be $S = 6V^{2/3}$.

Values of Q in front of the grille as a function of the dimensionless constant ka for the four entrance conditions shown in Fig. 11 are shown in Fig. 13. The quantity $k = 2\pi f/c$ where f is the mean frequency of the band of noise being considered and c is the speed of sound in ft/sec.* The quantity a is the radius of grille in feet if it is circular, or equals $L/\sqrt{\pi}$ if the duct is square with an area of $L^2 ft^2$. If the duct is rectangular with an area $L_x L_y$, the value of Q to be used lies between the Q's for two square ducts of areas L_x^2 and L_y^2.

For more accurate determinations of the sound pressure level, the factor $0.5 + 10 \log_{10} [(\sqrt{293/K})\ (B/30)]$ should be added to Eq. (8), where K = absolute temperature in degrees Kelvin and B is the barometric pressure in inches of mercury.

The second term of Eq. (8) is plotted in Fig. 14, with SPL in db as ordinate, distance from the duct opening as abscissa and the room constant R and the directivity factor Q as parameters.

It is seen from Eq. (8) and Fig. 14 that the noise from a ventilating duct is less at distances farther from it. Moreover, at large distances, the levels (averaged in space to eliminate standing waves) produced in the room depend only on the power level of the source and the room constant and not in the directivity factor and the distance r.

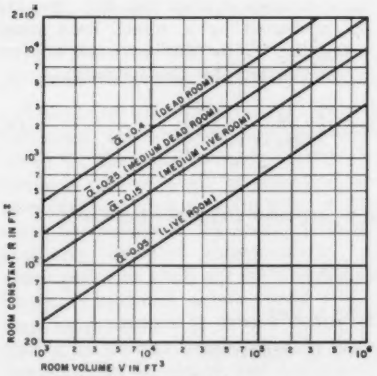


Figure 12

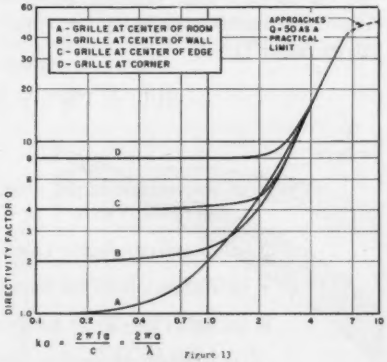

A - GRILLE AT CENTER OF ROOM
B - GRILLE AT CENTER OF WALL
C - GRILLE AT CENTER OF EDGE
D - GRILLE AT CORNER
APPROACHES Q = 50 AS A PRACTICAL LIMIT
DIRECTIVITY FACTOR Q
ka = 2πfa/c = 2πa/λ

Figure 13

*The speed of sound equals (1052 + 1.11°F) ft/sec where °F is the temperature in degrees Fahrenheit.

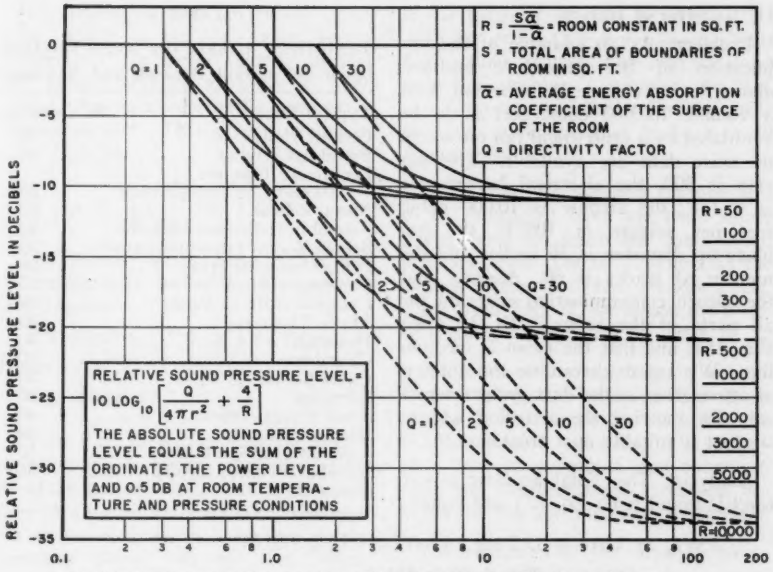

R = $\frac{S\bar{\alpha}}{1-\bar{\alpha}}$ = ROOM CONSTANT IN SQ. FT.
S = TOTAL AREA OF BOUNDARIES OF ROOM IN SQ. FT.
$\bar{\alpha}$ = AVERAGE ENERGY ABSORPTION COEFFICIENT OF THE SURFACE OF THE ROOM
Q = DIRECTIVITY FACTOR
RELATIVE SOUND PRESSURE LEVEL = 10 LOG$_{10}$ $\left[\frac{Q}{4\pi r^2} + \frac{4}{R}\right]$
THE ABSOLUTE SOUND PRESSURE LEVEL EQUALS THE SUM OF THE ORDINATE, THE POWER LEVEL AND 0.5 DB AT ROOM TEMPERATURE AND PRESSURE CONDITIONS
Q=1
2
5
10
30
R=50
100
200
300
R=500
1000
2000
3000
5000
R=10000
RELATIVE SOUND PRESSURE LEVEL IN DECIBELS
DISTANCE FROM ACOUSTIC CENTER OF A DIRECTIONAL SOURCE IN FEET = r

Figure 14

C. *Criteria*

The criteria for the design of ventilating systems is usually based on hearing requirements for speech in the room. For good hearing conditions the arithmetic average (in decibels) of the long-time RMS speech levels in the three octave frequency bands between 600 and 4800 cps should be greater than the *speech interference level.* The speech interference level is defined as the arithmetic average of the noise levels in those same three bands.[6] The assumption is made that the noise has a continuous spectrum.

Reference to Fig. 15 shows the complete criteria curves used by one consulting firm.[7] The SC numbers on the curve are equal to the speech interference level. In Table I we show the SC value that we believe ought to be chosen for particular cases that the ventilation design engineer may encounter in practice.

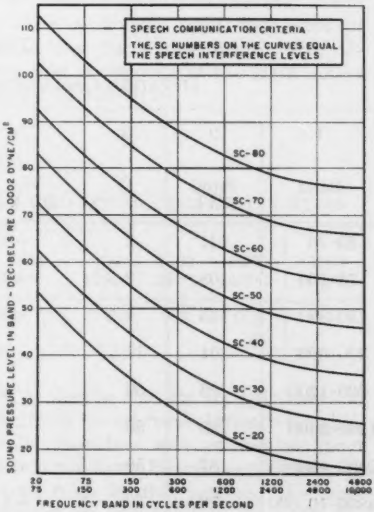


Figure 15

D. *Example of Design*

Problem: As an example of the application of the procedure outlined above, let us assume that a room with a volume 100,000 cubic feet is to be ventilated by a centrifugal fan on which no noise data are available. The fan rmp is 300, the electrical horsepower is 4 HP, the airflow is 10,000 cubic feet per minute at 100°F, the fan blade-tip diameter is 36 inches and the number of blades is 60. Assume that the speech communication criterion for all parts of the room is SC-35 (See Fig. 15), and that the room is medium live. We are to determine the amount of attenuation in the duct system necessary for meeting the criterion and to suggest a suitable duct treatment.

Analysis: The Total acoustic power level is found from Eq. (7) and equals,

$$\begin{aligned} \text{PWL} &= 120.4 + 17.7 \log (4/60) + 15 \log (60/6) \\ &= 120.4 - 20.8 + 15 \doteq 115 \text{ db.} \end{aligned}$$

The band power levels are found from Fig. 10, where we shall conservatively use the upper edge of the shaded area. The data are plotted in the second column of Table II. From Fig. 12 the room constant R equals about 2500 square feet.

TABLE I

TENTATIVE CRITERIA FOR NOISE CONTROL
(Courtesy of Bolt Beranek and Newman)

Type of Room	SC Criterion
Concert Halls	20
Broadcast Studios	20
Legitimate Theaters (500 seats, no amplification)	25
Music Rooms	25
Assembly Halls (amplification)	25
School Rooms (no amplification)	25
Homes (sleeping areas)	25
Conference Room for 50	25
Conference Room for 20	30
Movie Theaters	30
Hospitals	30
Churches	30
Court Rooms	30
Libraries	30
Small Private Office	40
Restaurants	45
Coliseums for Sports Only	50
Secretarial Offices (typing)	55
Factories	40–65

TABLE II

DETAILED CALCULATIONS FOR THE EXAMPLE

1 Band	2 Band PWL	3 Q	4 Fig. 12 DB Values	5 Colmns. 2+4	6 Criterion DB	7 Required Reduction DB
20–75	111	2	−25	86	67	19
75–150	108	2.3	−25	83	58	25
150–300	105	4.2	−24	81	50	29
300–600	101	17	−18	83	43	40
600–1200	96	50	−13	83	38	45
1200–2400	93	50	−13	80	34	46
2400–4800	87	50	−13	74	31	43
4800–10,000	79	50	−13	66	31	35

For operation with an SC-35 criterion, which is not (a) very severe (criterion), the grille velocity in feet per minute may be as high as 1000. Hence, the necessary grille opening is 10 square feet. This gives a value of a in Fig. 14.

$$a = \sqrt{\frac{10}{\pi}} = 1.78 \text{ ft.}$$

The quantity $ka = 2\pi fa/c$. Because the temperature is 100°F, the speed of sound equals

$$c = 1052 + 1.1°F = 1162 \text{ ft/sec}$$

Hence,

$$ka = 0.0096 f$$

From Fig. 13 we see that the directivity factor is lower when the grille is in the center of the wall than when it is at an edge or a corner. Also, we see that the grille will become fairly directive above 100 cps, i.e., when $ka > 1$.

Therefore, it is desirable to locate the grille high on the wall if possible in order to take full advantage of the directivity. Let us, however, assume the worst condition, where the grille must be at head level. Then Q will be as great as the values given by Fig. 13 (see column 3 of Table II). Of course, if the listeners are not directly in line with the grille, Q will not approach the high values assumed here and the noise reduction problem is simpler. In fact, at 45° to a perpendicular line the grille face, Q can be assumed to be 2 at all frequencies.

From Fig. 12, we find the numbers to be subtracted from the band sound power level to obtain the band sound pressure level. Let us assume that the nearest listener is 10 feet from the grille. Then from Fig. 12, we obtain the numbers given in column 4 of Table II.

Addition of the numbers in colums 2 and 4 gives the band sound levels in column 5. In column 6 we tabulate the SC-35 criterion numbers. The difference between column 5 and column 6 gives the required noise reduction between the fan and the room in decibels.

The reduction of the noise by 19 to 45 decibels will be possible by using a duct that is subdivided into cells. The number of the cells will depend on the length of the duct available for lining and on the thickness and type of acoustical absorbing material selected. Let us assume a typical rigid rock-wool or glass-fiber duct-lining board, with absorption coefficients in the eight octave bands as follows:—

TABLE III

ABSORPTION COEFFICIENTS FOR A 1-INCH THICK TYPICAL DUCT-LINING BOARD

Frequency Band	20 75	75 150	150 300	300 600	600 1200	1200 2400	2400 4800	4800 10,000
α	0.05	0.1	0.3	0.7	0.8	0.8	0.8	0.8

Parkinson[6] has presented the empirical chart given in Fig. 16 for relating the attenuation in decibels per foot to the absorption coefficient and the length of a duct side. Let us assume that 60 feet of duct are available to line. Also, let us assume that the acoustic losses in the three lowest bands through the sidewalls themelves will amount to about 0.1 db per foot. Hence, we will pick up about 6 db by this process. We must pick up an additional 13 db in the 75-

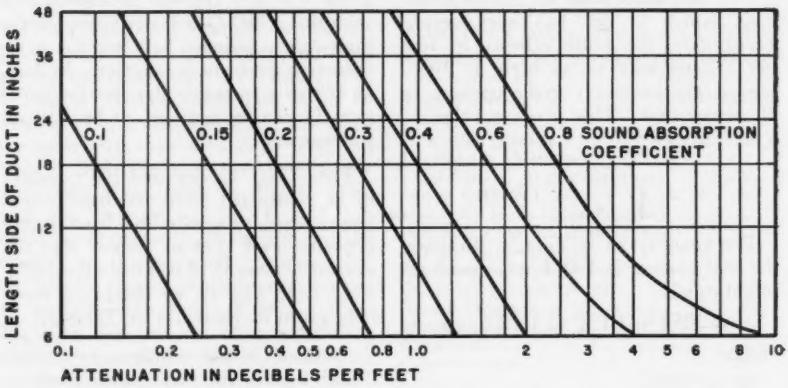


Figure 16

150 cps band. In the second band, we wish 0.3 db/ft loss. Reference to Fig. 16, shows that for $\alpha = 0.1$, we need to divide the duct by means of splinters into sections that are no wider than (about) 4 inches. This would require, of course, subdivision into 10 compartments if the duct were 40 inches by 50 inches (i.e., ten 4-inch components plus the material). At higher frequencies there would be no trouble in obtaining the necessary noise reduction because of the high values of the absorption coefficients.

More efficient acoustical absorbing structures than parallel baffles in the duct can be constructed using bends and plenums. These structures usually introduce higher back-pressure into the system and must be specifically designed.

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4. The authors are deeply indebted to Professor Robert W. Leonard, Physics Department, University of California at Los Angeles, for taking these data.

5. *Heating Ventilating Air Conditioning Guide*—Ch. 40—Sound Control, Vol. *30,* p. 871—1952—Amer. Soc. Heat. Vent. Engrs. New York City, New York.

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7. Bolt Beranek and Newman, 16 Eliot Street, Cambridge 38, Mass.

8. J. A. Parkinson, "The Prediction of Noise Levels From Ventilating Equipment," Heating and Ventilating, March 1939, pp. 23-26.

NOISE OF VENTILATING FANS

ACKNOWLEDGMENT

Like its companion paper, "Apparatus and Procedures for Predicting Ventilation System Noise," also reprinted in this issue of the JOURNAL, this paper was published in the March 1953 edition (Volume 25, No. 2) of "The Journal of the Acoustical Society of America." The authors were Lieutenant C. F. PEISTRUP, USCG, and Lieutenant (junior grade) J. E. WESLER, USCG, who performed the work on which this paper was based while engaging in post-graduate study at Massachusetts Institute of Technology.

This paper presents the results of acoustical measurements made on five commercially available ventilating fans. In performing these measurements use was made of an apparatus described in a companion paper.[1] Three vaneaxial fans[2] of different diameters and two centrifugal fans of different sizes were tested. In an attempt to generalize the results of these investigations, an empirical formula was derived that permitted the computation of the overall acoustic power levels expected from fans of known design characteristics.

The procedures adopted in using this equipment were arrived at by a process of trial and error, and are felt to offer a simple and efficient approach to the problem of measuring fan noise.

Through the cooperation of the Bureau of Ships, Navy Department, three U. S. Navy Standard vaneaxial-type fans were made available for testing, and with the cooperation of The Westinghouse Electric Corporation, Sturtevant Division, two commercial centrifugal-type fans were also tested. Characteristics of both types of fans are listed in Table I.

To test the various fans to determine their exhaust noise characteristics, each fan was run at about twelve different speeds, at an incremental speed of 200 rpm for the highest speed fans, and 50 or 100 rpm for the slower speed fans. Since most of the fans tested were driven by d-c motors, the various speeds were regulated by varying the armature current on the smaller fans, and the field current and field voltage on the larger fans. The lowest practicable speed of each fan was first determined, and the readings begun on the next highest multiple of the speed increment chosen. The speeds were measured accurately by means of a strobotac properly calibrated over the desired frequency range.

First, the overall level of the exhaust noise at each speed was determined. Then readings were taken successively through the twenty-four one-third octave frequency bands. At the end of each series, the overall level was determined again as a check. In addition, at each speed the electrical input power was determined. This procedure was used on the three vaneaxial-type fans connected directly into the apparatus as described in Ref. 1.

TABLE I

TABLE OF FAN CHARACTERISTICS

Fan Name	Fan Type	Rated Motor Speed	Rated Motor HP	Type Motor	No. Blades	Blade Tip Diam.
						inches
A½D1W5	Vaneaxial	3450	⅓	DC-Compound	7	10.5
A1½D1W5	Vaneaxial	3450	1¼	DC-Series	7	14.25
A2A2W5	Vaneaxial	3480	1½	AC-Induction	5	15.5
Silentvane	Centrifugal	*	*	DC-Series	10	30.0
Multivane	Centrifugal	*	*	DC-Series	60	40.25

* For these two Westinghouse fans, the motors were mounted separately from the fans and were not necessarily those used in an actual ventilating system.

All vaneaxial fans were U. S. Navy Standard type, and were on loan from the U. S. Navy.

The Multivane fan has forwardly curved blades while the Silentvane fan has backwardly curved blades.

For the A½ fan, at 3450 rpm, the airflow was about 900 ft³/min. For the A1½ fan, at 3450 rpm, the airflow was about 1950 ft³/min.

It was impossible to bring the two available centrifugal-type fans into our laboratory to make use of this apparatus directly. So the apparatus was adapted to the available conditions. The two fans were already connected to long lengths of circular duct, equipped with standard "egg crate" straighteners.[2] In order to obtain an anechoic termination, three large acoustic wedges of the type used in the original apparatus were installed temporarily in the exhaust end of these ducts. This temporary suspension was accomplished by bolting the three wedges together, forming a square base twenty-four inches on a side. To the base of these wedges were bolted two two-inch by four-inch boards, forming a large "X." These boards were then clamped temporarily to the flanges of the exhaust end of the ducts so that the wedges were in the center of the circular duct. Thus an effective anechoic termination was installed, and in addition, a moderate amount of back pressure was provided. No canvas vibration isolation collar could be readily installed in these ducts. However, since the fans were about forty feet from the position of the measuring microphone and the driving motors were mounted separately from the fans, it was felt that isolation was unnecessary. A small hole was drilled in the duct, and the same procedure as described above was followed in taking the readings.

For this problem, it seemed advisable to present the observed data in terms of power levels, in decibels.

$$\text{PWL} = 10 \log_{10} \frac{W}{10^{-13}}, \text{ db re } 10^{-13} \text{ watt} \qquad (1)$$

TABLE II

ADDITIONAL DATA FOR WESTINGHOUSE FANS

MULTIVANE				SILENTVANE			
RPM Speed	Elect. HP	Acoustical HP	Airflow ft³/min.	RPM Speed	Elect. HP	Acoustical HP	Airflow ft³/min.
150	0.995	0.375×10^{-5}	6,950	200	0.45	0.0482×10^{-5}	5,300
200	1.645	0.754×10^{-5}	9,260	300	0.92	0.375×10^{-5}	7,950
250	2.75	1.475×10^{-5}	11,580	400	1.71	1.33×10^{-5}	10,600
300	4.27	3.75×10^{-5}	13,890	500	4.02	3.09×10^{-5}	13,250
350	6.24	6.03×10^{-5}	16,200	600	4.85	9.51×10^{-5}	15,900

$$SPL = PWL - 10 \log_{10} S + 10 \log_{10} \left[\sqrt{\frac{293}{°K}} \left(\frac{B}{30} \right) \right] + 0.5 \text{ db re } 0.0002 \text{ microbar} \quad (2)$$

$$PWL = SPL + 10 \log_{10} S - 0.5 + 10 \log_{10} \left[\sqrt{\frac{°K}{293}} \left(\frac{30}{B} \right) \right] \text{ db re } 10^{-13} \text{ watt} \quad (3)$$

where:—

SPL = Sound Pressure Level in decibels
PWL = Power Level in decibels
°K = Absolute temperature in degrees Kelvin
B = Barometric pressure in inches of mercury
W = Power in watts
S = Crosssectional area of duct in square feet.

Power level is defined[1] as ten times the logarithm to the base ten of the ratio of the acoustic power in watts to the reference power of 10^{-13} watts—Eq. (1). Under standard conditions of temperature and pressure, this value is nearly numerically equal to the sound pressure level which this acoustic power would represent if it were passing uniformly through an area of one square foot. During this work, the atmospheric conditions were sufficiently close to standard to permit this latter relation to be used. Thus the acoustic power passing through ducts or areas of different sizes could be reduced to a common reference level, affording a basis for comparison and for further computations.

Using standard definitions, the sound pressure level observed in a duct may be converted to power level by use of Eq. (3).

To obtain sound pressure level directly from the instrumentation used, the corrections for each element of the overall system were compiled in decibels, and used as one overall correction. The microphone was calibrated in deci-

TABLE III

ADDITIONAL DATA FOR VANEAXIAL FANS

RPM Speed	A1½ D1W5 Elect. HP	A1½ D1W5 Acoustical HP	A1½ D1W5 Airflow ft³/min.	A½ D1W5 Acoustical HP	A½ D1W5 Airflow ft³/min.
1700	0.17	0.0188×10^{-5}			
1900	0.21	0.0483×10^{-5}		0.00603×10^{-5}	
2100	0.25	0.0483×10^{-5}		0.00765×10^{-5}	
2300	0.305	0.0483×10^{-5}		0.00951×10^{-5}	
2500	0.371	0.0764×10^{-5}		0.01208×10^{-5}	
2700	0.446	0.0764×10^{-5}		0.01475×10^{-5}	
2900	0.53	0.951×10^{-5}		0.0188×10^{-5}	
3100	0.62	0.1475×10^{-5}		0.02413×10^{-5}	
3300	0.73	0.1475×10^{-5}		0.0375×10^{-5}	
3450	0.90	0.188×10^{-5}		0.0375×10^{-5}	

For the A2A2W5 vaneaxial fan the Acoustical Horsepower is 1.21×10^{-5}, at its rated speed of 3450 rpm. The Electrical Horsepower for the A½D1W5 and A2A2W5 vaneaxial fans was not measured.

bels with respect to one volt output for a sound pressure of one microbar. Referred to the standard reference of 0.0002 microbar, a sound pressure of one microbar is 74 decibels. The correction for the center frequency of each one-third octave band was used as the average over that band. Thus by subtracting from 74 db the gain of the amplifier in db and the microphone calibration in db, and then adding the filter correction in db, we arrive at the overall correction for a particular frequency band. This correction is added to the meter reading to give the sound pressure level re 0.0002 microbar for that band. Thus, by reading the voltage output of the microphone system in decibels referred to one volt, the sound pressure level may be determined directly and, finally, the power level computed from this.

The results of the exhaust noise spectra measurements of the various fans are shown in Figs. 1, 2, 3, 5, and 6. This portion of the total data obtained is presented in the form of curves for visual convenience and should be self-explanatory.

An interesting result of these tests is the effect of varying back pressure on the exhaust noise spectra of these fans. The three vaneaxial-type fans were run at various speeds at back pressures ranging to about three inches of water. The result of this investigation for the A2A2W5 fan at rated speed is shown in Fig. 4. Similar results were obtained from the other two fans. Thus it was concluded that a change in back pressure has negligible effect on the noise output of a fan exhaust. This result was unexpected.

Following the completion of the exhaust noise measurements, the inlet noise characteristics of the three vaneaxial fans were measured. This work was done outdoors in an effort to approach free field conditions. The inlet noise spectra were similar to that of the exhaust noise, and the directivity characteristics were as expected.[3] See Figs. 7 and 8.

As a final phase of the ventilating fan analysis, an empirical formula was derived whereby the overall power level of the fan output can be predicted using common fan parameters:—

$$PWL = 120.4 + 17.7 \log_{10} (HP/N) + 15 \log_{10} (N/6) \text{ db re } 10^{-13} \text{ watt} \quad (4)$$

where:—

PWL = Overall power level in decibels (See Eq. 1)

HP = Total horsepower to fan

N = Number of fan blades

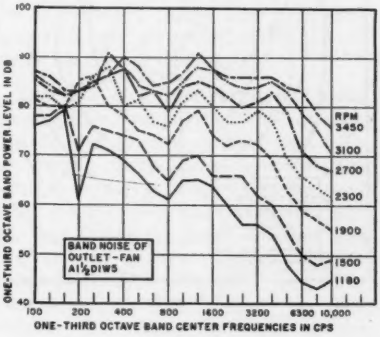

Figure 1

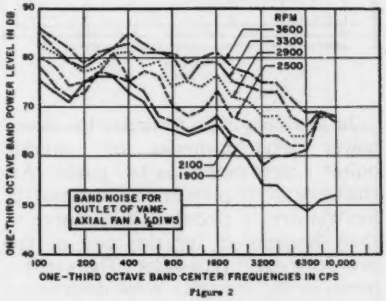

Figure 2

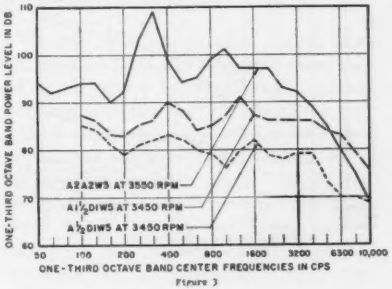
ONE-THIRD OCTAVE BAND POWER LEVEL IN DB
A2A2W5 AT 3550 RPM
A1½DIW5 AT 3450 RPM
A½DIW5 AT 3450 RPM
ONE-THIRD OCTAVE BAND CENTER FREQUENCIES IN CPS

Figure 3

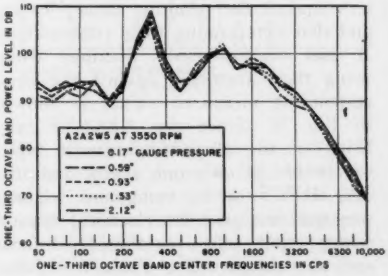

Figure 4

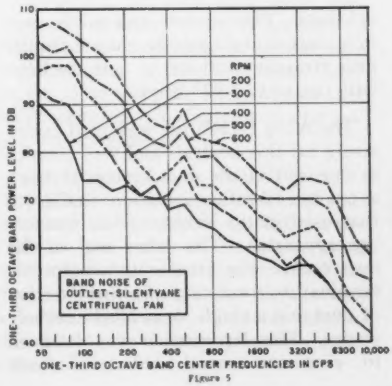

Figure 5

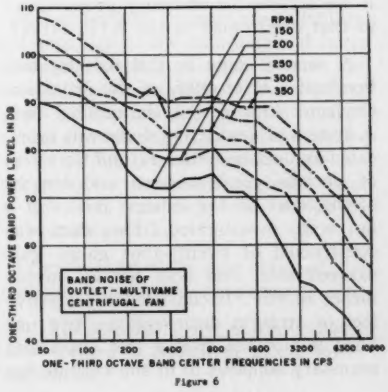

Figure 6

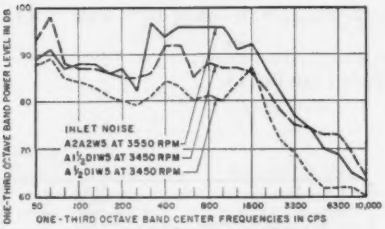
ONE-THIRD OCTAVE BAND POWER LEVEL IN DB
INLET NOISE
A2A2W5 AT 3550 RPM
A1½D1W5 AT 3450 RPM
A½D1W5 AT 3450 RPM
ONE-THIRD OCTAVE BAND CENTER FREQUENCIES IN CPS

Figure 7

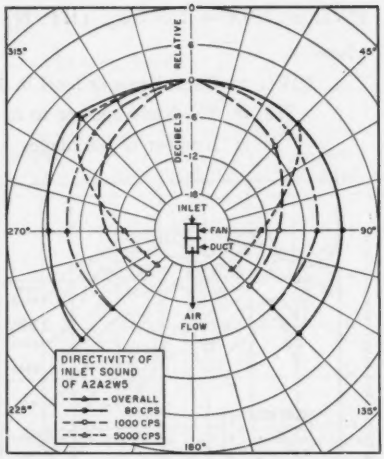

Figure 8

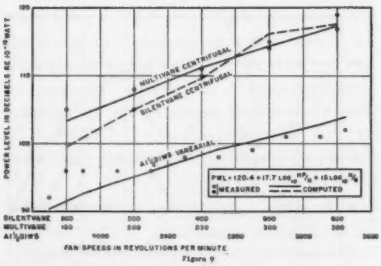

Figure 9

In deriving this formula, the basic power level formulas for aircraft noise[4] were used as a guide. An efficiency of 95 percent was assumed in the transfer of electrical horsepower to shaft horsepower for the case of the two centrifugal-type fans. The various terms in the formulas were determined by plotting the corresponding parameters against the resulting power levels, and thus determining their relationship. A plot of the results obtained from using these formulas against the corresponding measured values is shown in Fig. 9. Since the A2A2W5 fan, being of the alternating-current type, was tested at only one speed, and the A1½ D1W5, being compound wound, was not measured for electrical horsepower input, plots for these two fans are not shown. The A2A2W5 fan's power level value at its rated speed checked closely with the computed value if we assume an efficiency proportional to that determined in the A1½ D1W5.

A second stage in this investigation involved a brief study of the acoustical characteristics of a typical unlined duct. A system of ventilating ducts was fabricated and set up outdoors, and the effect of various configurations and lengths of this duct on the exhaust noises of a fan were investigated. This duct was constructed of twenty-four gauge galvanized steel and was ten by twelve inches in size. It consisted of forty-five feet of straight duct sections, two unlined 90° bends twelve feet apart and necessary adapters to fit the various fan exhausts. This system was fairly easy to transport and could be shaped readily into straight sections or into sections with one or two 90° bends.

The A1½ D1W5 fan was used exclusively for this analysis and was coupled to one end of the duct system through a canvas vibration isolation similar to that used in the exhaust noise measuring apparatus. The other end of the duct system was fitted with an acoustic termination consisting of a lined section of duct and a single suspended anechoic wedge. This termination was designed to eliminate sound reflections back

through the duct system and proved quite effective for this purpose.

Again, the same system of instrumentation was used to obtain the noise spectra. Here, however, the microphone was mounted on a small plywood sled, in such a manner as to least disturb the surrounding sound field. The sled permitted easy movement of the microphone inside the duct system.

The first step in this phase of the investigation was to find the attenuation of the straight unlined duct. To accomplish this, all sections of the straight duct were coupled together, and noise spectra were taken at intervals of five feet inside the duct. The fan was run at four different speeds only:— 1500, 2300, 2900 and 3450 rpm. The attenuation per foot of duct was then obtained by taking the slope of the curve of decibels plotted as function of distance along the duct.

To determine the effect of adding one 90° unlined bend to a straight duct, the last three power level readings (taken over the last ten feet of duct) in the straight duct and in the duct with the bend added were averaged for the four speeds. For each frequency band, the difference between the straight-duct power level and the 90°-bend power level gave the attenuation in decibels. The four sets of attenuation (one for each speed) for each band were then averaged, and the final average used as the value of attenuation in decibels due to the addition of one 90° unlined bend. In the same way, the effect of two such bends separated *twelve* feet in the system was determined.

The attentuation in decibels per foot in the ten by twelve-inch unlined duct is shown in Fig. 10. Note that the two peaks in the curve occur in the bands containing the frequencies at which the duct width equals $\lambda/2$ and $3\lambda/2$, where λ is the wavelength. Greatest attenuation is at the higher frequencies, as expected.

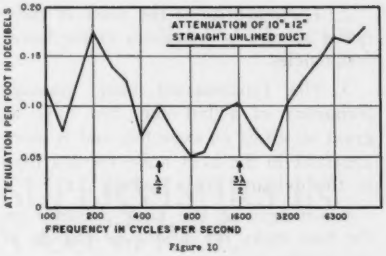

Figure 10

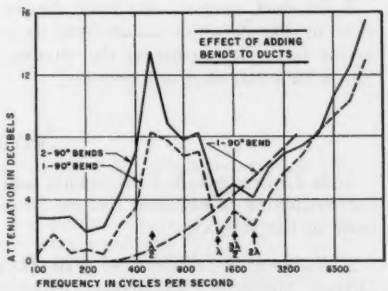

Figure 11

The effect of adding one or two 90° unlined bends is shown in Fig. 11. Here also the arrows on the curve show the frequency bands containing the frequencies at which the duct width equals multiples of $\lambda/2$, where again λ is the wavelength. The width of the duct is that in the direction of the bend.

It is difficult to evaluate the reliability and accuracy of the data obtained here, since this work represents a new approach to the problem of ventilating noises. Although the general consistency of the data indicates that the results are good, but the usefulness of the information to the design engineer must be the final yardstick with which to evaluate this work.

From a study of the data obtained, the following conclusions were drawn:—

1. The general shape of the exhaust noise spectra is contained in the lower frequencies.

2. The majority of the noise in these outlet spectra is contained in the lower frequencies.

3. The fundamental blade passage frequency of a fan does not have as great an effect as expected, and is more apparent in the inlet noise spectra than in the exhaust noise spectra.

4. Changes in the back pressure on the fans make no significant change in the frequency spectra.

5. In duct systems, the duct dimension in the direction of a bend is a major factor in predicting the attenuation which that duct will provide.

It is realized, of course, that the study of only five fans cannot be considered as final and conclusive. More work must be done in testing other fans and other types of fans. Such tests would also serve to confirm the accuracy and value of the derived empirical formulas. If these formulas could be approached in some way from a purely theoretical viewpoint, probably a much better check could be provided. It is hoped that this work provides new information for acoustical and ventilation design engineers and will encourage and form a basis for further investigation in this subject.

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3. L. L. Beranek, *Acoustic Measurements,* J. Wiley and Sons (1949) p. 253, Fig. 5.57c.

4. H. W. Rudmose and L. L. Beranek, "Noise Reduction in Aircraft," Jour. Aero. Sc. *14,* p. 79, Feb. (1947). See also "Sound Control in Airplanes," Jour Acous. Soc. Amer. *19,* p. 357, (1947).

TRAINING SHOP SUPERVISORS IN PRODUCTION CONTROL

DR. GERALD PAUL STONE

THE AUTHOR

DR. STONE has been a civilian employee of the Navy Department since 1941. Among the positions he has held are Marine Engineer, Philadelphia Naval Shipyard and Naval Architect, Assistant for Production, and Industrial Engineer, New York Naval Shipyard. He is now the civilian supervisor of the Planning Office, Naval Supply Depot, Bayonne, New Jersey. During World War II, Dr. Stone worked with the New Construction Planning and Scheduling Group at the New York Naval Shipyard on the CV33 class. After war he continued his research and wrote his thesis on this subject, receiving the Doctorate from New York University in 1949.

The author of this paper had the pleasure of training shop supervisors in production control at the New York Naval Shipyard. The experience proved so gratifying and the results were so beneficial that he feels it worth while to record his impressions.

This course stemmed from the joint interest of management and the men actively participating in production control in the various shops of the Production Department to improve their performance through training. Accordingly, the author, at that time an Industrial Engineer at the Yard, was assigned the task of preparing and presenting a course of training for supervisors and shop planners on this subject.

At the very onset it was realized that this problem required careful consideration of the following points:

1. It would have to be designed to meet the needs of those taking the course.
2. Its approach would have to be fundamental and grounded in the basic principles of production control.
3. The aspect of training would have to be stressed so that the students could make use of this course in their day to day work.
4. The course would have to be sold to the supervisors and shop planners to gain their acceptance and support.

With these points in mind, the first step in the preparation of the course was to hold a meeting with the representatives of the shop supervisors and planners to determine what they considered desirable to be included in the course. The masters of the shops in-

OUTLINE OF PRODUCTION CONTROL COURSE

UNIT 1

1.1 Entrance Inventory
1.2 Introduction to production control—principal elements
1.3 Objectives of course
1.4 Principal elements of industrial engineering
1.5 Unit review & related applications to shop work

UNIT 2

2.1 Production analysis
2.2 Operation sequence
2.3 Job analysis cards
2.4 Routing
2.5 Standardization
2.6 Manpower & material requirements
2.7 Principle of exceptions
2.8 Unit review

UNIT 3

3.1 Material control
3.2 Status of material report
3.3 Principle of exceptions
3.4 Plans, B/Ms, jigs, fixtures, tools
3.5 Unit review

UNIT 4

4.1 Scheduling
4.2 Overall scheduling—prediction of future workload
4.3 Master scheduling
4.4 Detail scheduling
4.5 Principle of exceptions
4.6 Machine loading
4.7 Unit review

UNIT 5

5.1 Dispatching & progressing—I
5.2 Schedule revisions
5.3 Workload balancing
5.4 Dispatching board
5.5 Principle of exceptions
5.6 Unit review

UNIT 6

6.1 Dispatching & progressing—II
6.2 Principle of exceptions
6.3 Gantt Charts
6.4 Quality control
6.5 Unit review

UNIT 7

7.1 Work simplification
7.2 Principles of motion economy
7.3 Process charts
7.4 Methods improvements
7.5 Unit review

UNIT 8

8.1 Cost control
8.2 Types of work
8.3 Budgetary control
8.4 Unit review

UNIT 9

9.1 Application of production control to CV34
9.2 Application of production control to Shop 36
9.3 Production control forms
9.4 Production control project—specific shop applications

UNIT 10

10.1 Naval Shipyard Orders
10.2 Production Department Memoranda
10.3 BuSandA Manuals
10.4 Final inventory

FIGURE 1

volved were given a similar opportunity to comment on the proposed course. Interviews were then held with the various activities at the Shipyard engaged in production control. This included discussions with the design engineers, planners and estimators, scheduling group, and material procurement section. In addition, a fairly extensive review was made of the published literature on production control, with particular emphasis on fundamental principles and applications to shipbuilding.

After due thought, it was finally determined that the course would center about the following principal elements—production analysis, material control, scheduling, dispatching and progressing. In addition, the historical development of the science of production control and a brief mention of the principles of work simplification, quality control, cost control, Shipyard directives on the subject, and applications to ship construction and shop manufacturing would round out the course. The outline of the course as finally prepared is given in Figure 1.

It was decided to present this course as a series of ten two hour lectures and ten two hour seminars. Lectures on the subject, round table discussions, films, textbooks, current technical articles and individual projects, applying the basic principles of production control to actual jobs within the shops, were all used in this training course.

The course finally began on a hot summer day in July. Thirty shop supervisors and planners assembled in a room in the training division at the Shipyard. It was interesting to observe the faces of the men who made up this group. They were all experienced artisans and supervisors from the shipfitter, sheet-metal, forge, boiler, electric, pipe, woodworking, machine and other shops in the Production Department. While considerable effort had been made to sell this course in advance, it seemed to the instructor that the real selling job would either succeed or fail as he began to talk on the subject of production control. These practical men seemed to be saying "show us."

At the end of the first session, the author already noted that he had stimulated their interest in this subject. It is believed that this was accomplished through his attitude:

Let us sit back quietly in this classroom and analyze the concepts, fundamental principles and practices of production control. I am not an expert. Rather, you gentlemen are, but I want you to consider with me this complex subject as it applies to shipbuilding. Together we will examine this field and see whether we can improve our practices by our joint thinking.

The course ran for four months from July through November. Meetings were attended twice a week during regular working hours. Tuesday mornings there was a lecture on the subject matter for that week to the entire group of thirty participants. Wednesday and Thursday mornings were set aside for seminars to amplify the discussion of the lecture for the week, with 15 men in each group. The seminars were subdivided into two groups—one primarily structural and outfitting trades; the other, primarily machinists and related tradesmen. An opening inventory test was given to the students at the first session and the same test was repeated near the close of the course. This was done to provide an approximate evaluation of the material learned in this course.

Use was made of many training aids. Movies were shown, large posters, concerning the current topic, were placed on display, notes were distributed each week, and textbooks, technical articles and pamphlets were loaned to the participants for supplementary reading. Most importantly, each participant was asked to prepare a project applying the basic principles of production control to

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FIGURE 2

an actual job being worked within his shop. This project was then presented to the class by each participant and many lively discussions and ideas were forthcoming.

During the course it soon became evident that the shop supervisors and shop planners had many real problems of production control which they wanted to solve. An opportunity was given them to present these problems to top management. To simplify the procedure for presentation, a "State the Problem" memorandum was adopted. This was a convenient method of presenting to their shop masters in writing, problems affecting their activities. The shop masters, upon endorsing the forms, submitted them for the consideration of the Production Officer. The participants in this course made use of this procedure in bringing to the attention of management problems dealing with production, planning, material and scheduling.

Three films were shown to the class: "Planning and Laying Out Work," "Principles of Motion Economy," and "Statistical Quality Control." They demonstrated current application of these subjects. The first film was obtained from the U. S. Office of Education, "Principles of Motion Economy" from the Industrial Engineering Department, University of Iowa, and the third film was shown by representatives of the Johns-Manville Company who produced it. The films were all well received by the class.

The following books and pamphlets were used in the course:

1. "Production Handbook"—Alford and Bangs.
2. "Production Control"— Knowles and Thomson.
3. "Plant Production Control"— Koepke.
4. "Motion Study Applications"— Barnes.
5. "Manpower Utilization Through Production Control"— Metropolitan Life Insurance Co.
6. Various American Management Association Pamphlets.

A bibliography of recommended outside readings on production control was distributed to the class. This is contained in Figure 2.

Throughout the duration of this course, the instructor observed that training of shop supervisors must proceed with the understanding that they already know a great deal about the subject; considerably more than the instructor in their own particular area. Thus he learned that his task primarily was to stimulate their creative thinking, provide a medium for group discussion and make available to the participants certain techniques, such as the use of the Gantt Chart, principles of motion economy and the differentiation between over-all, master and detail scheduling.

The most vital single element in production control is production analysis. Thus, if the job is properly analyzed at its very beginning, with the proper sequence of operations, tools, manpower requirements and material needs, the effective control of production is assured. Therefore, considerable emphasis was given to the breaking down of jobs into their main components.

As previously noted, each participant prepared a project applying these principles to a real job in his shop. Each student explained his project to the class. It was found beneficial to use a projector, flashing the writeup on the screen. Very lively interest developed during these sessions and many constructive comments were offered by the other members of the class. In fact, the members of the group asked for a two week extension of the course to allow complete discussion of these projects. They stated that it was very beneficial for them to see how the other

PRODUCTION CONTROL—EVALUATION OF COURSE

It is requested that you assist in the evaluation of this course. The results of this evaluation will aid in future sessions of this course. Do not sign your name. It would be preferred if your answers are typed. Please answer the following questions. Add whatever comments you feel are applicable.

1. What is your opinion of the content of this course?
2. How could the content of this course be improved?
3. What is your evaluation of the method of presenting the course material?
   a. Lectures
   b. Seminars
   c. Notes
   d. Text books
   e. Films
4. How could the presentation be improved?
5. Do you feel that the instructor is qualified?
   a. Technically—on Production Control
   b. As a teacher—in presenting information
6. Has this course met your needs in your capacity as a shop supervisor or shop planner? (Please indicate which you are)
7. How could it more fully meet your needs?
8. Do you feel that this course ought to be repeated?
9. If yes, then whom do you recommend as participants?
10. This course consists of ten major topics. Next to each one please add your comments on the content, presentation, and value.
    a. Introduction—General Summary of Subject
    b. Production Analysis
    c. Material Control
    d. Scheduling
    e. Dispatching
    f. Progressing
    g. Work Simplification
    h. Cost Control
    i. Applications of Production Control
    j. Pertinent directives
11. Please add whatever comments you feel are applicable.

FIGURE 3

shops were applying production control. The instructor's role at this point was mainly that of moderator. He guided the questioning and demonstrated the applications of the principles of production control to the various projects presented.

Toward the end of the course an evaluation sheet (Figure 3) was given to each member. He was asked to give the instructor the benefit of his comments on this training course. Unanimously the class agreed that the course ought to be repeated, and they recommended that the other departments in the Shipyard and all top supervisors be given this training. They ranked the seminars as most valuable with the lectures a close second. The films, lecture notes and textbooks were considered next useful in that order. They felt that the course had met their needs and was helpful in the performance of their work. The lectures were ranked in this order—production analysis, applications, dispatching and progressing, material control, work simplification, scheduling, cost control, introduction, and pertinent directives.

The final session of this class is an event that will long be remembered by the author. The men assembled in a large conference room, all smiling and friendly. It is believed that they had been shown that production control can be treated on a scientific basis and that through careful thought and application of basic principles, their work can be improved. The Shop Superintendent, President of the Shop Masters Association and the Head of the Procedures Branch addressed the group. Certificates were given to each participant.

It was concluded that there were direct and indirect benefits from this course. The direct benefits of subject matter learned can be gaged by the average grades of the opening and final examination—47% and 82%. Indirectly, it was noted that the interest of the participants had been stimulated to further improvements on their own in their various shops. The work of the Procedures Branch, sponsoring the course, was greatly aided by this training since production control as an operating concept gained greater acceptance. Recently the master of one of the large shops was visited and there on his desk was a set of lecture notes for the production control course. He said that he was studying them. Numerous other requests for the lecture notes were received.

Thus, it is believed that supervisors can successfully be trained in production control. It is not an easy task, but the results are well worth the effort.

WORSHIP OF THE BMEP AND THE NEW MAN ENGINE

P. H. SCHWEITZER

THE AUTHOR

Professor in Charge of Diesel Research, The Pennsylvania State College, received his M.E. degree from the Technical University of Budapest and his Dr. Eng. degree from the Technical Institute of Dresden. He came to this country in 1920 and, after working for the DeLaVergne Machine Company and General Motors Corporation, joined The Pennsylvania State College in 1923 as Assistant Professor of Engineering Research and became Professor of Engineering Research in 1936. At that institution he has initiated and conducted research on diesel engines and related subjects ever since. For 25 years Dr. Schweitzer also acted as consultant to prominent diesel manufacturers on design and development. Since 1952 he has been Partner in Schweitzer & Hussmann Engineering Office, Engine Designers and Consultants, while maintaining his connection with The Pennsylvania State College.

He is a member of American Society of Mechanical Engineers, Society of Automotive Engineers, American Society of Naval Engineers, Coordinating Research Council, Society of Sigma Xi, and Fulbright Scholar 1953-54.

Dr. Schweitzer is author of a book, "Scavenging of Two-Stroke Cycle Diesel Engines," and well over a hundred papers and articles on engines, sprays, instruments, fuel testing, high altitude lubrication, etc.

The new highly supercharged MAN engine, Type KV*, has aroused worldwide attention and deservedly so. It was shown for the first time, and attested by such recognized authorities as Professors Eichelberg and Pflaum that an internal combustion engine can produce power at the unbelievable low fuel consumption of 0.31 lb. per bhp/hr, corresponding to a thermal efficiency of 45%, at 231 psi continuous bmep. These figures are truly amazing and justly raise the question: is the Navy justified to continue relying on the two-stroke cycle engine for the propulsion of most of its vessels, or should it adopt the highly supercharged, high bmep, four-stroke cycle engine in its stead.

* Described in the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS, August 1952, pages 512-538.

TABLE I

	Bore and Stroke in.	No. of Cyl.	Displ. Volume cu. in.	Rated rpm	Rated hp cont.	Hp/ cu. in. displ.	Hp/ sq. in. piston area	Weight, dry lbs.	Specific Wt., lb/hp	Height x Length x Width, in.	Space Required cu. ft.	Hp/ cu. ft.	Spec. fuel cons. lb/bhp hr at rated hp
MAN K6V 4-stroke	11.8 x 17.7	6	11,620	400	1270	0.11	1.94	40,000*	31.5*	128 x 140 x 60	625	2.03	0.313
GM 12-278 A Marine, 2-stroke	8.75 x 10½	12	7,577	750	1230	0.162	1.7	24,000	19.5	109⅞ x 154¼ x 57	560	2.2	0.39
GM Electromotive 16-567B, 2-stroke Locomotive	8.5 x 10	16	9,100	800	1680	0.185	1.85	30,500	18.15	88 x 212$\frac{11}{16}$ x 62$\frac{3}{16}$	675	2.49	0.382
GM 6.71, 2-stroke Marine	4.25 x 5	6	427	1600	130	0.307	1.53	2,645	20.4	40¼ x 63⅜ x 33½	53.4	2.43	0.42
FM 10-38D8-⅛ Marine, 2-stroke	8.125 x (10+10)	10	10,370	720	1600	0.154	1.54	34,000	21.2	116½ x 226$\frac{15}{16}$ x 57½	878	1.82	0.37
Krauss-Maffei KMD6, Truck 2-stroke	4.72 x 5.12	4	360	2200	145	0.403	2.07	1,579	10.9	44 x 35 x 36	32	4.55	0.38
Packard 1D-1700 Marine, 4-stroke	5.625 x 6.250	12	1,704	2000	600	0.352	2.0	3,300	5.5	54$\frac{3}{16}$ x 85$\frac{11}{16}$ x 41$\frac{5}{16}$	111	5.4	0.38

* Without Blower.

In deciding this question intelligently it should be helpful to analyze the MAN accomplishment from the following viewpoints:

1. What specific features were responsible for those excellent results?
2. Do those results indicate that engines of the new MAN type will have superior over-all performance and suitability for naval operation?

Except for general refinements in design and workmanship the MAN Type KV engine had only the following unconventional features:

1. The supercharge by the turboblower was raised to 2.35 atmospheres. (33.3 psia).
2. Effective intercooling of the charging air was used.
3. Crossheads were employed, unusual in a 11.8″ bore engine.

It is readily seen that none of these features are inapplicable to two-stroke cycle engines. The choice of the four-stroke cycle was defended on the basis that the thermal load and stresses were lower and could be handled with an uncooled piston. The question whether piston cooling represents a less desirable complication of the engine than, for instance, the addition of crossheads is at least debatable.

The most important *output* values of a powerplant are horsepower per pound weight and horsepower per cubic foot space. Engines are frequently appraised on the horsepower output per cubic inch piston displacement and/or on brake mean effective pressure. The writer wishes to make the point that the latter indices are false measures of the specific power output of an engine. Engineers became so embroiled with bmep that the latter emerged as the most respected index in evaluating an engine. But the ship, its captain and its operating crew pay no attention to the bmep. They want power which makes speed. Whether the high power is produced by high bmep or by other means is immaterial. In turbines bmep does not even have a meaning.

In anticipating such criticism the authors of the article show a comparison among four different means by which the engine output can be increased from 1000 to 3000 hp, and prove that tripling the bmep is preferable to tripling the rpm with a corresponding decrease in cylinder displacement and increase in cylinder number. Changing the number of power strokes per revolution was not considered. However, what ultimately counts are pound weight per horsepower and cubic foot space per horsepower. Table I shows a comparison of the new MAN engine with other high output engines, several of which are in naval use.

In this table engines of widely varying sizes and speeds are listed. A slow-speed engine like the MAN should not be compared with a small high-speed engine, the life expectancy of which is much shorter. The MAN is relatively slow even on the piston speed basis, which is probably necessitated by the use of a crosshead.

Comparing the new MAN engine with another marine engine of similar power output we find that the MAN engine weighs 31.5 lb/hp compared to the GM 12-278A 19.5 lb/hp, and it puts out 2.03 hp per cu ft space compared to GM's 2.2 hp per cu ft. The comparison with smaller cylinder displacement engines is still less favorable, which, however, is understandable because the specific output (hp/cu in. displacement) approximately is in inverse ratio to the bore.

The new MAN engine is an experimental rather than a production engine. It represents a remarkable accomplishment as it shows the way to very high bmep's and very low fuel consumptions. With equally refined design and grade

of workmanship similar performance can, no doubt, be achieved in production engines, but whether such high grade of workmanship is practically obtainable in production has not yet been demonstrated.

The design features that are obviously responsible for the outstanding performance are high supercharge, high efficiency turbine and blowers, intercooling and crosshead construction. All of these features are applicable to two-stroke cycle engines and most of it with presently available skill and materials.

The power output of any listed two-stroke cycle engine could be increased substantially by adopting a more efficient blower. By improving the blower efficiency from 60 to 70% adiabatic, 6% could be gained in power output. The 9-stage-axial-centrifugal blower used by MAN surely exceeds 70% adiabatic efficiency. In adopting turbocharging, the practicality of which has been recently demonstrated by the Burmeister & Wain turbo-charged 7500 hp two-stroke cycle engine in Tanker *Dorthe Maersk* which has completed its shakedown cruise, 35% increase in bmep was obtained without reduction in rotative speed.

By moderate intercooling, which would reduce the inlet air temperature from 60 F above ambient to 30 F above ambient, another 6% could be picked up.

A better exhaust system using "aspirator type" exhaust manifolds can easily add another 3% to the power output.

By these steps the present 92 psi bmep (cont.) of a uniflow engine can be increased to 135 psi and the present 75 psi bmep of the loop-scavenged engine to 110 psi, without reducing the rotative speed or the engine life. The specific output per pound weight or cubic foot space would increase in almost the same proportion.

Therefore, if the two-stroke cycle is ahead now in specific power output it will be still more ahead when these design advancements will be applied. There is, however, another recent development which is more suitable to two-stroke cycle than to the four-stroke cycle, that is turbo-cooling.

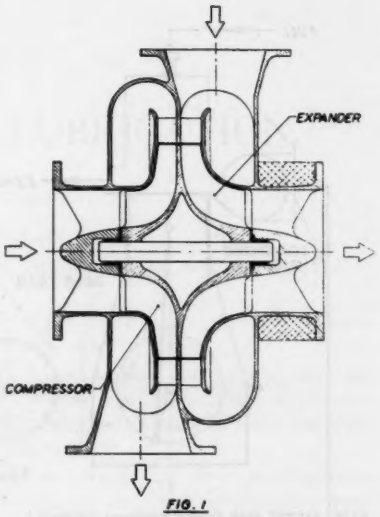

FIG. 1

Turbo-cooling is the name of a cycle in which the engine intake air is cooled by expansion by passing it through an air turbine. It was originated by Mr. H. A. Steiger, now with Sulzer Bros. Co. in Switzerland.

Turbo-cooling has already been successfully applied to the cooling of aircraft compartments, where its compactness makes it attractive even though the work produced by the turbine is unused. However, the air turbine is also efficient in doing work while it cools the air. In the Steiger cycle a centripetal air turbine (the expander) is coupled with a centrifugal blower (the compressor), the two forming an integral unit as shown in Figure 1. This unit is connected to the intake system of an engine. Figure 2 shows the connection in a simple installation to an unsupercharged two-stroke cycle engine

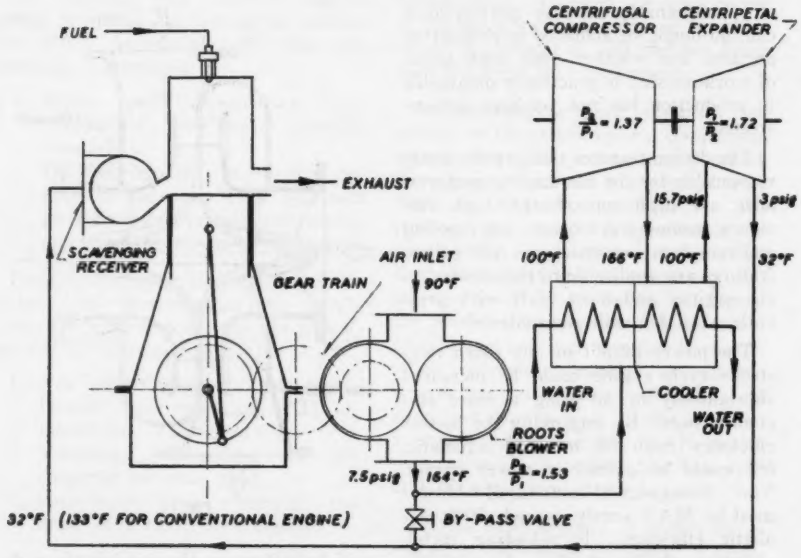

FIG. 2

in which case the turbo-cooling boosts the engine output by 20 to 30% without increasing the heat load on the engine.

With the design improvements listed, the specific output of the two-stroke cycle engine can easily be increased by 60% without sacrificing simplicity and reliability.

As to fuel consumption, the spectacular figures measured on the new MAN engine have never been duplicated. But some two-stroke cycle engines have come fairly close to it. In 1934 on a Sulzer 5500 hp loop-scavenged marine engine, Eichelberg measured a specific fuel consumption of 0.326 lb/bhp-hr. In 1946 on a Crossley 3-cylinder 10½ × 13½, 600 rpm, loop-scavenged engine, H. Desmond Carter measured 0.355 lb/bhp-hr. On opposed piston uniflow Junkers aircraft engines similar low fuel consumptions have been recorded. The writer has measured on a Krauss-Maffei 145 hp, 4-cylinder loop-scavenged truck engine, a fuel consumption of 0 342 lb/bhp-hr. These were all production rather than experimental engines. With due respect to MAN's 0 31 lb bhp-hr, the difference is not so decisive as to compensate for the relatively low specific output. And this difference may easily get lost or turn negative when the MAN engine gets into production.

If we view the MAN development from the proper perspective, admiration is due for the accomplishment, but we need not get unduly excited about it and alarmed about its practical consequences. The U. S. Navy has followed a sound path in its diesel engine development program.

NEW IDEAS ON LUBRICATION

ACKNOWLEDGMENT

This article, written by BÖRGE LUND appeared in the April 1953 issue of "The British Motor Ship."

Based on his belief that it has never been possible to find a simple method for the evaluation of bearing properties, the author over a period of 15 years has carried out investigations and experiments, as a result of which he puts forward some new hypotheses which may be briefly summarized as follows:

1. The function of a sleeve bearing is conditioned by the formation of adhesive films, which prevent metallic contact between the rubbing surfaces. *These films are produced by a chemical reaction between the rubbing metals, the lubricant and the surrounding atmosphere.*

2. *The bearing properties of a metal* are determined by the ability of its surface under sliding to react with the lubricant and the surrounding atmosphere for the formation of adhesive films which prevent metallic contact between the rubbing surfaces.

3. *The lubrication ability* (*oiliness*) of a lubricant is determined by the ability of its components under sliding to react with the metal surfaces and the surrounding atmosphere for the formation of adhesive films which prevent metallic contact between the rubbing surfaces.

Full details of the investigations which led to these conclusions were presented by the author to the Danish Academy of Technical Sciences and they have been published in the Transactions of the Academy. This forms an extensive treatise of 130 pages and a summary of this work is given in the following article.

It is laid down as fundamental that in order to give satisfactory service, a good sleeve bearing must be lined with a suitable bearing metal and lubricated with a suitable lubricant. If one of these factors is neglected, the sliding properties of the bearing will be considerably reduced. Sleeve bearings have been used for a very long time, and it may be mentioned that one of the first patents on bearing alloys was taken out by Isaac Babbitt in the 1830s, hence the name "Babbitt's Metal" commonly used in the English-speaking world.

THE THEORY OF LUBRICATION

The observations of Tower, a British railway engineer in 1883 were developed by the mathematician and physicist, Reynolds, and became the basis of the widely-used hydrodynamic lubrication theory. The principle is that the relative movement between shaft and bearing draws the oil forward into a wedge, which interposes itself between the sliding surfaces, thus preventing metallic contact. This did not explain the necessity of using special bearing metals.

In a hydrodynamically working bearing the sliding surfaces are separated by a fluid layer of lubricant and this condition is called "fluid lubrication." The loss of energy in the bearing in this state is essentially determined by the internal friction in the lubricant.

Where the lubrication layer does not fully separate the sliding surfaces so that there is partial metal contact, the state of lubrication is called "boundary lubrication." The loss of energy depends partly on the fluid friction in the lubricant layer and partly on the sliding conditions between the metal surfaces.

The lubricants normally used, the mineral oils, have no direct possibility of forming protective films on the sliding surfaces and no chemical reaction between metal and lubricant is known. This may explain why it is necessary to use special bearing metals. Yet it is obvious that a closer investigation of the problem of bearing properties will have to start from boundary lubrication conditions where there is the greatest possibility of intimate reaction between lubricant and bearing material.

Under conditions of boundary lubrication high temperatures may be expected at the points of metallic contact, and this combined with the high pressures, the violent deformation and the fresh metal surfaces, will give greater possibility of chemical reaction, especially when the influence of the atmosphere is taken into consideration. By introducing the atmosphere and especially its content of oxygen as a third party to the lubricant/bearing metal combination, which is generally forgotten because the atmosphere is always rare, it is evident that chemical reactions are possible.

Accepting as a fact that the interaction between the lubricant and the bearing metal is most marked under conditions of boundary lubrication, a simple test method has been developed by the author based on controlled boundary lubrication. A plain piece of the bearing metal is used as a test piece and a ball-bearing ball fixed in a chuck is employed as the sliding element. The test piece is submerged in the lubricant and the ball is pressed against the test piece under constant load. The ball is caused to reciprocate over the test piece by means of a connecting rod and the speed is 72 rpm, which gives 144 starts per minute. The stroke is 127 mm, the the maximum speed being 0.5 m per second.

While the load on the ball is constant the specific load at the point of contact depends on the width of the track worked into the test piece. It is demonstrated that good metal/oil combinations produce the narrowest track. For white metal the specific load in the track will be of the order of 12,000 to 15,000 kilos per sq centimeter (17,000 to 21,000 psi), while for copper alloys it may rise to over 4000 kg per sq centimeter (55,000 psi).

The ball chuck is insulated from the test piece and current at low voltage is passed through so that it is possible to follow the resistance in the track developed by the reciprocating movement of the ball over the test piece. A cathode ray oscillograph is used and a recording voltmeter registers the change of the mean voltage at the measuring point.

The chief purpose of the lubricant is to prevent metallic contact between the sliding surfaces and it is possible by this method to follow the state of lubrication as tests proceed. In order to obtain a simple expression of this condition the mean voltage curve is measured in such a manner as to show during what part of the test period there is electrical contact between the sliding surfaces.

This value is named the L value and the lower it is the better is the bearing metal/oil combination. Comparing the results with practical experience for bearing metals, it is proved that the

lowest L values are found when using the best bearing metal.

If, therefore, the oil is maintained constant, the method may be employed for a systematic evaluation of the bearing properties of the metal and if the bearing metal is constant, the method may be correspondingly used for measuring the lubrication qualities of the lubricants.

RESULTS

Analyzing the results which have been obtained by the author, it is found that the films developed under boundary lubrication processes are of crucial importance for attaining fluid lubrication, which indicates that boundary lubrication is the primary effect, while fluid lubrication is a welcome secondary effect.

It is further established that quickly solidified tin-base or lead-base white metal possesses better bearing properties than slowly solidified metal of the same compositions. An aging of quickly solidified metal will, however, slightly reduce the bearing properties. An aging of the lubricants, on the other hand, seems to improve the lubricating characteristics.

A suitable degree of oxidation seems to be necessary to obtain lubricant films. This is counteracted when the lubricant contains anti-oxidants. The necessity of suitable oxidation has been confirmed by investigations of semi-conductor effects in and outside the track on a white metal sample. It proved that far greater amounts of oxide-containing substance were found in the track than outside.

Lead appears to be one of the alloying constituents in white metal which, to the greatest extent, promotes the formation of a strong film, while phosphorus has a correspondingly very strong effect on copper alloys.

The contents of these substances in the lowest melting phases are of prime importance. So far as the tin base bearing metals are concerned, high tin alloys containing a little lead possess better bearing properties than the corresponding lead-free alloys. By aging the alloys the difference is still more marked. In the lead-free alloys the solid solution of the matrix forms the lowest melting component. By aging, the chemical reaction ability of the super-saturated solid solution is considerably reduced. The lead-containing tin-base alloys may further contain a still lower melting phase; the lead containing eutectic. The composition of this does not change essentially by aging, and it therefore maintains its chemical reaction ability relatively unchanged. As the lead-containing alloys, however, also contain super-saturated solid solution with reduced reaction ability after aging, the total effect will be a slight decline, although not so much as for the lead-free alloys.

The tests have shown that the reaction necessary for the formation of a film presumably consists in an oxidation of the oil promoted by the lowest melting components of the bearing metal, which probably act as oxidation catalysts. This reaction will take place at the points of contact between the sliding surfaces and it is here that the maximum reaction possibilities are to be found: high pressure, high temperature, strong deformation and fresh metal surfaces. The film developed should presumably be of a solid consistency in order to yield the best possible protection against metallic contact.

The friction in the bearing depends partly on the fluid friction in the lubricant, and partly on the friction in the oil film itself. Here the frictional loss consists of two factors: the friction in the film and the metallic friction in the points of contact. If the film is soft,

the film friction will be low, because the shear strength of the film is low. The metallic friction, on the other hand, will be essential because the possibility of metallic contact is greatest through the soft film. If the film is of a more solid nature, the metallic friction will be of less importance.

In the former case the loss of energy by friction will chiefly take place at the metal, thus probably causing a breaking-up of the surface. In the latter case this possibility is not so great, and here it must be presumed that the loss of energy will be chiefly absorbed by building up the lubricating film.

It must, therefore, be considered to be of vital importance that the film is of such a consistency that it prevents metallic contact and promotes "fluid" lubrication at the speeds generally occurring in the bearing in question. The "wounds" arising through metallic contact should instantaneously be "healed" by the formation of film.

It is considered by the author that the principles thus established carry the bearing phenomena into the category of chemical boundary surface processes. These principles must also apply to several phenomena of wear and, for instance, by studying the possibilities of wear on piston rings and cylinder liners it would be necessary to include details concerning the composition and structure of all the materials concerned. Much too often only a single group of the components which are participating in the boundary surface processes in question are investigated, and this may cause quite misleading results to be obtained.

The test method which the author has developed is simple in execution and relatively easy to apply. It takes about one hour to test a metal/oil combination after a suitable preparation of the sample. The method has, moreover, shown good reproduceability for all the metal/oil combinations investigated. About 200 different alloys and 25 to 30 different lubricants have been tested.

The subject is, however, so extensive that it would require many years to investigate fully all existing compositions. The author's thesis should, therefore, be considered as the commencement of a long range of further investigations. In this respect it is suggested that there should be widespread participation in the investigations.

It is felt by the author that one thing has been attained: it has been possible to ascertain an interaction between bearing metals and lubricant, and it has been possible to express this interaction by one figure. This opens up so many possibilities that the method or similar methods based on the same principles might be considered of significance for future studies of bearing and lubrication processes.

No doubt the oxidation requirements, as outlined in this thesis, will be met with opposition on the part of oil chemists who are usually of opinion that it is just the oxidation that is the cause of many difficulties in the lubricants. Nevertheless, the hypothesis possibly contributes to a better understanding of the conception of "oiliness." It will, perhaps, be difficult for lubrication chemists to accept the idea that boundary lubrication processes are of decisive importance, even when the lubrication is practically fluid, but this assertion can hardly be disregarded when the properties of the bearing metal are taken into consideration.

ON THE FUNDAMENTALS OF THE BOUNDARY LAYER THEORY

ACKNOWLEDGMENT

This article, published in the April 1953 edition of the "Journal of The Franklin Institute," was written by M. Z. KRZYWOBLOCKI, of the Panel on Fluid and Solid Mechanics, University of Illinois.

INTRODUCTION

As is well known the engineering sciences were created by means of some combination of more fundamental scientific fields such as mathematics, physics, chemistry, etc., with the special purpose of enabling one to apply in a very direct way the fundamental results to highly practical problems of immediate use. At the beginning of the existence of those sciences, an engineer used to follow more or less precisely the paths of reasoning of such a fundamental field like, say, mathematics. But in the course of years, his way of reasoning began to deviate more and more from the rigorous logic of mathematics. Being anxious to supply an immediate result, he began to use his initiative and sense of invention to create various methods of solutions of differential and integral systems without proving the existence and uniqueness theorems at all. Sometimes these proofs were derived by pure mathematicians after the engineer proposed the method, as was the case with the Heaviside calculus. Sometimes the proofs presented by an engineer did not make any sense, as was the case with the so-called Principle of Least Work Method in the theory of elasticity. In the 20th century the situation became still worse, due to the fact that the number of such "engineering" solutions increased beyond human imagination. The situation became paradoxical, particularly when the large engineering circles with an inadequate mathematical background believe in preposterous proofs cited in various text and handbooks written by other engineers of a similar theoretical background. A good example is the so-called Principle of Least Work Method, where rigorous mathematical proofs do not succeed in convincing engineers that the method has weak mathematical justification and is only a random choice method. It may be that the engineer is unable to follow the mathematical derivations and stubbornly preserves his tradition simply because no other better method is available. On the other hand, a mathematician wonders why the word "mathematics" is abused by an engineer, why it is not preserved only for the field whose logics and derivations follow the principles of mathematics in the fully rigorous meaning of this word and why

some other name was not invented for those manipulations consisting of some simple operations like differentiation, integration, etc., which are used by an engineer without any rigorous justification, having the only confirmation in form of physical experiment.

Below, the author will discuss the fundamentals of the boundary layer theory. In particular, he will show that there does not exist any rigorous mathematical theory of the boundary layer due to the lack of solution of the corresponding boundary value problem of non-linear partial differential equations. A discussion on the fundamental equations underlaying the boundary layer theory in hypersonic flow will close the present note.

PRANDTL'S PROPOSITION

Prandtl (1904) proposed and Blasius (1908) worked out the first approximate solution of the boundary layer equation along a flat plate situated horizontally for an incompressible fluid with a constant coefficient of viscosity. The fundamental Prandtl's assumptions based upon physical observations were the following: (*a*) the boundary layer thickness is very small (which is true at moderate velocities in a high density medium); (*b*) as a consequence of (*a*) the vertical velocity component in the boundary layer is negligible and may be assumed to be almost equal to zero; (*c*) as a consequence of (*a*) and (*b*) the gradient of the pressure in the vertical direction is almost equal to zero; (*d*) as a consequence of (*a*), (*b*) and (*c*) the resultant velocity in the potential flow outside the boundary layer is horizontal and equal to the uniform velocity of the incoming flow. Prandtl put forward the hypothesis of a certain "metric" of the boundary layer in an incompressible flow in form of the thickness of the boundary layer δ proportional to $Re^{-\frac{1}{2}}$, with Re denoting the Reynolds Number. These assumptions allowed Prandtl to reduce the number of equations from three to two and to reduce the number of terms in one of the two remaining equations. From physical tests it was noticed that the velocity distribution in the boundary layer is similar to a parabola. This suggested to Prandtl the use of a transformation function $z = \text{Const. } yx^{-\frac{1}{2}}$, which function transforms the system of the reduced non-linear partial differential equations onto a system of ordinary differential equations in one independent variable z, solvable by the use of power series expansion, say. But neither Blasius nor anybody else after him did prove the existence and the uniqueness of the boundary value problem in question in a rigorous way.

DEVELOPMENT OF SOLUTIONS OF THE BOUNDARY LAYER

Prandtl-Blasius solution was and is followed by numerous methods of solutions of the boundary layer problem. All of them are formal procedures without going into the details of the existence and uniqueness of the actual boundary value problem. In the realm of a compressible fluid one may distinguish the following groups of methods of solution: (*a*) transformations that work under suitable simplifying assumptions about the parameters μ (viscosity), ρ (density) and κ (heat conductivity). One may include here the methods of von Mises, Crocco, Hantsche-Wendt, Howarth and others; (*b*) transformations that adapt the compressible boundary layer equations to the application of approximate methods developed for the incompressible boundary layer (Pohlhausen, etc.); (*c*) transformations that prepare the equations for a

numerical computer. One may include here series expansions, mostly power series which automatically imply the analyticity of the functions in question, propositions by Howarth, Hartree, Emmons and Brainerd, asymptotic solutions, etc. Concerning the asymptotic solutions the authors do not present the consideration on the order of the boundedness of the remainder which item mathematically is the most important since it may indicate how large is the discrepancy between the asymptotic solution and the actual value of the function in question. In all the methods mentioned above the existence of the solution is taken for granted.

BOUNDARY VALUE PROBLEM

Let us discuss the possibilities of proving the existence and uniqueness of the boundary value problem of the boundary layer. Assume that the heat factor is also taken into account, that is, the equations of state and energy are included. In this case the most general system of the boundary layer equations represents a system of non-linear higher order partial differential equations with (at least) two-curve boundary conditions (inner—at the surface of the body—and outer boundary curves).

As is known, the problem arising with such a differential system is to find, from the entire class of solutions of the differential system that solution or those solutions which satisfy certain additional conditions. Since problems of this type arise from physical considerations, certain properties are expected of the solution: (i) existence of a solution; oversufficient conditions should not be applied as they may be incompatible and no solution will be found. Existence of a solution may not always be assured by physical intuition; (ii) uniqueness of the solution; sufficient conditions should be provided to determine the solution uniquely; (iii) the solution should depend continuously on the data; this is necessary for a physical problem as the boundary and boundary values can be ascertained only within a small latitude of variation (the so-called "natural" problems). One may consider two possibilities:

(i) The possibility of solving the boundary value problem as a problem from the theory of partial differential equations. Let us discuss briefly these possibilities. As is known, the boundary conditions by mean of which one can determine a unique solution of the partial differential equation of the second order are of different character, depending upon the type of equation: elliptic, hyperbolic or parabolic. The classical theorem of Cauchy-Kowalewsky attempts to introduce a certain uniformity in the approach to the solution of such equations provided all the functions in question are analytic. But this uniformity in the approach ceases to be valid when the hypothesis of analyticity does not hold in the problem in question. Let us exclude from our consideration the parabolic type as being completely exceptional. Regarding the elliptic type the data may generally be expressed in one of three standard forms: (*a*) on a closed boundary S the value of the function u is specified (the boundary value problem of the first kind or that of Dirichlet); (*b*) on a closed boundary S the value of $\partial u/\partial n$ (or any of the first partial derivatives) is specified (the boundary value problem of the second kind or that of Neumann); (*c*) "mixed" boundary value problem, that is, choosing u on one part of S and its first partial derivative on another part of S. In some problems one can consider a certain linear combination of the two above data.

The second order partial differential equations of the "normal" hyperbolic type fulfill exactly the theorem of Cauchy-Kowalewsky. On an open curve

(initial curve) which may be finite, the values of u and $\partial u/\partial n$ are specified. This is a Cauchy problem. Generally, there are two curves joining the initial curve, going up to infinity, on which either u or $\partial u/\partial n$ are given (boundary curves). Hadamard mentioned that for the non-normal hyperbolic type no solution of the type mentioned above ("correctly set") is known. It is of importance to notice that in general, the elliptic type of equation usually does not admit the given data in form of Cauchy which are fully admissible for the hyperbolic type. Inversely, in the latter case it is of disadvantage to assume a closed curve which is convenient for the elliptic type.

The higher order equations "totally" elliptic (all the characteristic directions are imaginary) usually involve the following data: u and $\partial u/\partial n$ are specified along a closed curve or on a closed surface (Hilbert, E. E. Levi, Fredholm). The "totally" hyperbolic equations (all the characteristic directions are real) have been solved by Holmgren (by the Riemann method). The "composite" type of equations (characteristic directions partly real, partly imaginary) has been attacked by Hadamard

$$\left(\frac{\partial}{\partial x}\Delta u = \Delta\frac{\partial u}{\partial x} = 0, \frac{\partial^4 u}{\partial x^4} - \frac{\partial^4 u}{\partial y^4} = 0\right),$$

Sjöstrand, Davis

$$(b_1 u_{xxx} + b_2 u_{xxy} + b_3 u_{xyy} + \ldots = 0),$$

etc. The data are usually formulated in the following way: Let T be a closed subset of R, with a rectifiable boundary W. Let $W' \subset T$ be a curve extending from W to W: given u on W and $\frac{\partial u}{\partial x^2}$ on W', or u on W and W' or u_x on W and u on W', etc. Although such an equation is neither of pure elliptic nor hyperbolic type, one is compelled to assume that the equation should possess the properties of an elliptic character, which implies that one of the curves must be closed. To systems of first order equations one may refer the problem of Cauchy or initial value problem (one curve).

From this brief discussion it seems obvious that one cannot expect a solution of boundary layer problem in this group, that is, when the boundary conditions are formulated in the usual way on two curves:

(a) $y = 0, u = v = 0;$

(b) $y = \infty$ or $y = \delta, u = U_0,$
$v = \partial u/\partial y = 0.$

The boundary curves intersect at an angle, of course.

(ii) The possibility of a transformation of partial differential system into an ordinary one will be discussed next. For the sake of the simplicity we restrict our consideration to two independent variables. Assume a function $W = f(x, y)$ in two independent variables $\{x, y\}$ subject to a formal transformation into $\{x, y\}$ independent variables. Following the principles of classical analysis one obtains:

$$W = f(x, y) = F(u, v); \quad J = J\left(\frac{\phi, \psi}{u, v}\right); \quad x = \phi(u, v); \quad y = \psi(u, v);$$

$$u = g(x, y); \quad v = h(x, y); \quad f_{,x} = \begin{vmatrix} W_{,u} & W_{,v} \\ \psi_{,u} & \psi_{,v} \end{vmatrix} J^{-1}; \quad f_{,y} = -\begin{vmatrix} W_{,u} & W_{,v} \\ \phi_{,u} & \phi_{,v} \end{vmatrix} J^{-1}.$$

Moreover, the following relations will be used:

$$dy = d\psi = \psi_{,u}du + \psi_{,v}dv; \quad du = dg = g_{,x}dx + g_{,y}dy; \; dv = dh = h_{,x}dx + h_{,y}dy.$$

Introducing the latter two equations into that one for dy gives the expression of the form: $dy = (\ldots)dx + (\ldots)dy$. Since the variations dx and dy are independent and arbitrarily large, the first coefficient must vanish and the second must be equal to one. This gives two relations:

$$\psi_{,u}g_{,x} + \psi_{,v}h_{,x} = 0; \quad \psi_{,u}g_{,y} + \psi_{,v}h_{,y} = 1.$$

As the first condition we require that $u = \phi = x$, which implies

$$\phi_{,u} = 1; \quad \phi_{,v} = 0; \quad J = \phi_{,u}\psi_{,v} = \psi_{,x}; \quad g_{,x} = 1; \quad g_{,y} = 0;$$
$$f_{,x} = W_{,u} - W_{,v}\psi_{,u}/\psi_{,v} = W_{,u} + W_{,v}h_{,x}; \quad f_{,y} = W_{,v}/\psi_{,v} = W_{,v}h_{,y}.$$

As the second condition we require that $W = F(v)$ only, which implies $u = 0$ or $=$ const., $W_{,u} \equiv 0$, $x = \phi = 0$ or $=$ const., $\psi_{,u} = 0$. One gets:

$$f_{,x} = \frac{dW}{dv}\, h_{,x}; \; f_{,y} = \frac{dW}{dv}\, h_{y}.$$

But the Jacobian $\left(J\dfrac{(\phi, \psi)}{u, v}\right)$ vanishes identically and the transformation is not one-to-one. Let $v \equiv z = y/f(x)$, f being arbitrary. Thus the functions $f_i(x, y)$ $(i = 1, 2, \ldots, n, \ldots)$, satisfying a given system of non-linear partial differential equations $\theta_i(x, y, f_i, f_{i,x}, \ldots) = 0 (i = 1, 2, \ldots)$, are transformed onto the functions $F_i(z, x)$ belonging to a certain class (C), satisfying a system or ordinary differential equations $\Gamma_i = 0$, by means of some transformation function $z = z(x, y)$, fulfilling the conditions mentioned above. The transformation from partial derivatives in the (x, y, f_i)-space into ordinary derivatives in the $(x', z, F_i(z, x'))$-space, with $x' \equiv x$, is the main feature of this procedure. In the transformed system there appear only ordinary derivatives with respect to z. This means that x in $\Gamma_i = 0$ must be a parameter and also that the transformation is not one-to-one. As mentioned above, in the case of partial differential system one deals with a two-curve boundary value problem. In the case of an ordinary differential system one has a two-point boundary value problem. As is known, certain results were obtained in problems of this kind.

(iii) The boundary conditions will be discussed next. In the regime of an incompressible fluid or in the regime of a compressible fluid at low Mach Numbers the Prandtl's postulates can be accepted to be valid. This means that the boundary conditions on both boundary curves are well defined and given, the boundary layer is relatively very thin and the vertical pressure gradient is equal to zero. However, in the regime of a hypersonic flow in a rarefied gas the situation is different. One may distinguish here two sub-regimes: (a) hypersonic flow in a rarefied gas in continuum and (b) in slip flow. In the first one the inner boundary conditions may be assumed to be given, that is, the velocity is zero at the surface of the body. But the boundary layer is thick, sometimes very thick, in which case the vertical velocity component and the vertical pressure gradient inside the boundary layer are no longer of a negligible magnitude and definitely must be taken into account. This is the reason that the number of equations cannot be reduced. The vertical velocity component produced by the viscous flow at the outer edge of the boundary layer itself generates the external pressure field. The boundary conditions at the outer edge of the boundary layer are not given in the form of a definite number, but in form of a function which depends upon the (unknown at the beginning) solution of

the non-linear boundary layer equations. Such a type of a "non-linear" (as one may call it) boundary value problem appears more and more often in fluid mechanics. But, as is well-known, there is at present no solution to that problem and the only possibility is to apply some approximative iteration approach. In one of his papers, the author suggested a method of successive approximations. The situation complicates in a slip flow. In this case the inner boundary conditions are also "non-linear." For example, the slip velocity at the surface of the body is given by the expression $u|_{y=0} = C(u_{,y})_{y=0}$. The picture complicates almost beyond any hope if one includes the shock phenomena at the leading edge of the body. There may be required the boundary conditions of one type at the surface of the body (possibly non-linear), of another type behind the leading-edge shock (these may be given by the phenomena existing behind the shock) and still of another type (maybe non-linear) on the outer boundary curve. The outer boundary curve may not coincide with the shock curve, it may only intersect it.

A rigorous solution of the boundary value problem of the boundary layer phenomenon is the first fundamental problem.

FUNDAMENTAL EQUATIONS OF THE BOUNDARY LAYER

In general, one may distinguish two main regimes in the flow of a gas: Clausius regime, $K = d\lambda^{-1}$ being large (the symbol d denotes a characteristic dimension of the body and λ the free path) and Knudsen regime, K being small. Notice that there are authors who define the number K as equal to λd^{-1}. One may include in the first regime the mechanics of continua (the fluid sticks to the surface of the body) and the slip flow; the second regime may refer to the region of free molecule flow (Newtonian flow). The region of a rarefied gas may be contained partly in both regimes. Further, in both regimes the free path is assumed to be of such a length that the binary collisions are sufficient to describe adequately the phenomena in question. Of course, the question remains open whether the binary collisions are always sufficient; the phenomena at the front of the body in motion, near the stagnation point, may require a revision of that assumption.

As mentioned above, Prandtl and Blasius proposed a certain approximate solution of the boundary layer problem along a flat plate in an incompressible fluid. In the course of years their approach was extended to include curved surfaces, temperature pattern and compressible fluids. All those approaches were fundamentally based upon the assumption that the Navier-Stokes equations of motion (momentum) and energy (derived by means of concepts of the mechanics of continua) are adequate enough to describe the phenomena in question. But recently the flights at very high altitudes have been considered, that is, in hypersonics and in the range of a rarefied gas, or in other words, in the upper part of the Clausius regime, where both types of flow-continuum and slip flow may occur. In connection with that the question arises whether the Navier-Stokes equations are adequate enough to describe accurately the phenomena in that range. Let us discuss briefly this question.

The only other possibility is to refer to the kinetic theory of gases. As is well-known, the Maxwell-Blotzmann equation refers to a monatomic gas. A particular solution of this equation was proposed in works of Hilbert, Enskog, Chapman and others, and is known under the name of Burnett's equation. A certain generalization of Burnett's equation to polyatomic gases (beginning

with the Maxwell-Boltzmann equation) was proposed by C. S. Wang-Chang and G. E. Uhlenbeck. They derived only the first order terms for a polyatomic gas. As is known, the derivation of higher order terms in Burnett's proposition requires a great amount of time and energy.

These approaches preserve always the physical notions of the coefficients of viscosity and heat conductivity, as they are used today. There are various objections against Burnett's equations. Truesdell proposed a purely formal series expansion of the continuous function of several variables expressing the values of the shearing stress tensor and heat flux vector. The coefficients in these expansions are gradients of gradients. Hence they are new in physics and are unknown for the time being, unless some physical experiments in the future will be performed to determine them. Grad recently proposed another particular solution of the Maxwell-Boltzmann equation by use of Hermite polynominals. This is considered today to be the best method. But, in general, due to the lack of the general theory of non-linear equations one may be unable to investigate the influence of various parameters and assumptions upon the final form of the solution in question. Hence it may be difficult, today, to decide in an absolute manner which particular solution of the Maxwell-Boltzmann equation describes in the best way the physical phenomenon of the boundary layer, say, in the hypersonic regime, unless a great number of particular examples is solved by means of high speed computing devices, so that the general theoretical trend of the considered form of solution is visible. The question may become more complicated when other physical phenomena than those included in the solutions discussed above, will be taken into account. The possible very high temperature gradient in the boundary layer, which occurs in the flow in a hypersonic regime, jointly with the high speed of flow may originate such phenomena as ionization, dissociation, condensation and difference in electromagnetic charges. Moreover, the relaxation phenomena (establishment of equilibrium between the translational and the internal energy states when the former is changed by some process, for example, by a collision) should be necessarily included. Concerning the appearance of the dissociation phenomenon, the opinion is divided, although there are some who say that it does not take place in the boundary layer. The recent investigations at Cornell University proved that there appear significant electromagnetic phenomena in shocks due to a difference in electric charges. As is known, the phenomenon of a shock resembles closely the phenomenon of the boundary layer (steep variation in the velocity, temperature, and density distribution) and as Ludford recently had shown, the equations of a shock are in their certain phases, analogous to the equations of the boundary layer. The above phenomena are predominantly completely ignored in the existing forms of equations of the boundary layer. Some considerations on the subject of the dissociation phenomenon were presented by L. L. Moore. Some consideration of the subject of the relaxation time are contained in the British A.R.C.R. and M. Report by Gunn and in the report by C. S. Wang-Chang and G. E. Uhlenbeck, mentioned above. A certain initiative in the direction of considering the electromagnetic phenomena was undertaken by B. E. Howard in his thesis (University of Illinois), although the fundamental equation assumed is that of Navier-Stokes, in which a few new terms are added.

The Knudsen regime is, as yet, more or less in the sphere of speculations. The usual assumption is that the Newton's law of resistance is valid and that the physical picture in question is the model proposed by Newton: the parti-

cles hit the surface of the body and bounce backward.

The next question is the form of the equation of state. As is known, the basic hypotheses of the kinetic theory of gases as ordinarily presented restrict the validity of that theory to ideal gases ($p = R\rho T$). The question arises, of course, whether the status of the real gas in all the realms in question can be adequately described by the equation of state in the form $p = R\rho T$, $R = \text{const.}$

To all the controversial items discussed above, one more may be added. In 1951 Slezkin and Vallender (USSR Academy of Sciences) published two papers in which they attacked the ordinary, well-known, equation of continuity. Their reasoning is as follows: In the usual continuity equation one takes into account the density changes due only to the microscopic velocities but not to diffusion, whereas in treating the energy transfer both the convective heat transfer and the molecular phenomenon of heat conduction are considered. In their opinion the equation of continuity should be revised and after doing that they obtained new forms of equations of continuity, motion (momentum) and energy. One item must be strongly emphasized, namely, that the present form of the continuity equation as well as all the other equations of motion and energy can be derived from the Maxwell-Boltzmann equation. Slezkin and Vallender based their approach upon the usual assumptions of the mechanics of continua. Recently Šapošnikov criticized this hypothesis of Sleskin and Vallender and concluded that it does not correspond to a physical reality.

The establishment of definite, fundamental equations of motion and energy valid in the boundary layer, based upon sound physical assumptions, containing all the physical phenomena, discussed above, which are considered to be of a certain importance for the distribution of the velocity, temperature and density in the boundary layer, is the second fundamental problem of the boundary layer phenomenon of today.

FINAL REMARKS

The author discussed briefly above the two fundamental problems of the boundary layer phenomenon: the existence and uniqueness theorems and the fundamental equations governing the velocity, temperature and density distributions in the boundary layer. It seems that the existence theorem can be derived by means of the available methods of mathematics of today, but that the same cannot be said concerning the uniqueness theorem. Hence one is unable to state whether or not the boundary conditions as usually given by the physical principles are sufficient to determine the solution uniquely. Regarding the fundamental equations governing the velocity and temperature distributions, the opinions are divided and no conclusions can be reached without a considerable number of numerical examples to be calculated by means of high-speed computing devices.

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Photograph Courtesy J. M. Voith, Heidenheim

The Voith-Schneider Wassertrecker Turning in Its Own Circle.

A RADICAL DEPARTURE IN THE CONVENTIONAL TUGBOAT DESIGN, AND A NEW USE FOR CYCLOIDAL PROPULSION

LIEUTENANT COMMANDER W. E. FULLER, USN

THE AUTHOR

The author laid out, developed and is currently operating the Ship Repair Facility, Bremerhaven, Germany. Previous to this assignment he was a Staff Officer in the Pacific Reserve Fleet and prior to that Repair Superintendent in the initial development and operation of the Ship Repair Facility, Yokosuka, Japan.

During the war he was engaged in the construction of advanced base, shop and staging area facilities for Commander Submarines Southwest Pacific and the West Australian Indian Ocean Patrol Wing. Previous work connected with cycloidal propulsion involved Bureau of Ships experiments with the Kirsten propeller at Puget Sound Naval Shipyard.

CYCLOIDAL PROPULSION

INTRODUCTION

It is a well known fact that vessels equipped with screw propellers do not have adequate steering control when operated at low speeds and in restricted waters. This is because the rudder, to be effective, must react against a reasonable velocity of flow which can only be furnished when the ship is in motion. This is one of the reasons why most large vessels entering or leaving a port find it necessary to call on the assistance of port tugs as a safe means of ship handling.

The conventional tug is of comparatively large dimensions to ensure lateral stability and maintenance of a good steering way. His towing hook is positioned close to the midships section and well above the center of gravity. The propeller thrust placed into effect at the stern is considered to be in unstable equilibrium with respect to the towing forces so that continuous manipulation of the helm is necessary in order to maintain the desired direction of pull on the tow. With the towing hook well above the center of gravity the vessel tends to heel over when the pull is not in the fore-and-aft direction and for this reason it is important that sufficient lateral stability be incorporated in the vessel's design. To provide this condition a wide beam is called for along with sufficient length and draft for good holding qualities. All of which results in a large and comparatively high-priced vessel having objectionable unstable equilibrium of forces.

In order to operate a tug efficiently and at an economical cost the following features must be considered:

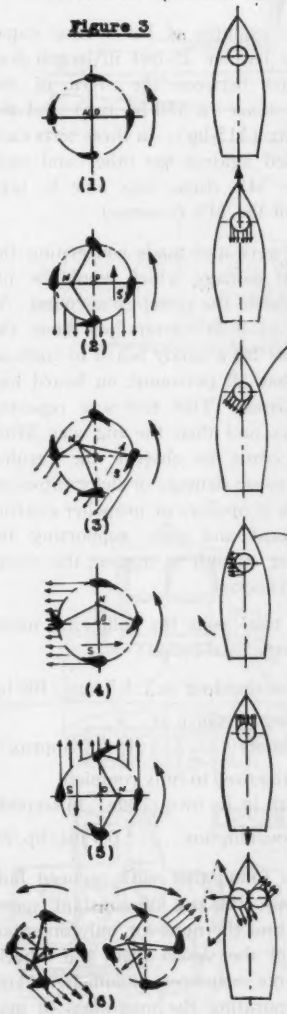
1. Reduced hull dimensions to a permissible minimum.
2. Low construction cost.
3. High maneuverability.
4. Positive stability.
5. Large towline pulling capabilities.
6. Adaptability to any towing requirement.
7. A minimum operating crew.
8. Low operating costs, i.e., fuel, lube oil, crew members, etc.

NEW TUGBOAT DEVELOPMENTS

The firm J. H. Voith of Heidenheim, Germany, which pioneered the development of cycloidal propulsion in Europe, has been working for the past two years on a new principle in tugboat design. By utilizing the well known Voith-Schneider cycloidal propulsion unit and positioning it forward of midships, with the towing point at the stern, he considered that a stable equilibrium between the propeller thrust and towline pull would be possible as a result of the linear arrangement. Repeated turning of the helm is eliminated since the rotating propulsion unit easily maintains the tug in a prescribed circle regulated, or controlled, by the direction of propeller thrust. Thus, the hull is not greatly influenced by forces created in the towing operation, such as a heeling tendency, resulting in a vessel of considerably reduced dimensions.

In this design cycloidal propulsion is essential, since, with it propeller thrust can be changed to any direction independent of engine or vessel speed and will be equal in magnitude in any direction to that of the forward thrust. The direction of movement is instantaneous since the tug is at the center of forces free to move in any direction. See Figure 3 for an explanation of this principle of operation of a cycloidal propulsion unit.

Figure 3



PRINCIPLE OF OPERATION OF THE VOITH-SCHNEIDER PROPELLER

Figure 3 shows diagrammatically the Voith-Schneider propeller. Several aerofoil shaped blades are installed on a circular rotating table with the shaft of the blades inside the table linked to an adjustable control point N. If point N is at center O (1) and the propeller is rotated in the direction of the arrow the blades remain tangential and no propeller thrust is produced.

If point N is moved in the direction shown in (2) the leading edges of the blades on the forward half of the propeller orbit will swing outwards while those on the other half will turn inwards. On the forward half the blades throw the water into the orbit while those on the other half throw the water outside the orbit thereby producing the propeller thrust. The force of the thrust depends on the degree of oscillation of the blades, i.e., the pitch, which is a measure of the movement of point N.

The magnitude of the thrust and thus the speed of the vessel is infinitely adjustable from full speed ahead to full speed astern without changing the revolutions or direction of rotation of the engine and propeller. Control is from the bridge by means of a speed lever (pitch control) and a steering wheel (directional control).

The direction of the thrust is always at right angles to the line O-N. If N is moved in any other direction the thrust changes accordingly as illustrated in (3), (4) and (5) where the propeller thrusts are shown in Figure (3). Their corresponding actions as installed in a 'Water Tractor' are (1) Stop, (2) Ahead, (3) Turning to stbd, (4) Turning to stbd on the spot, and (5) Astern.

With two Voith-Schneider propellers (6) both thrusts can be directed so as to produce a resultant transverse thrust to the ship causing it to move sideways with or without a ship in tow.

A PILOT MODEL IS DEVELOPED

To prove his theories Mr. Voith had a pilot model constructed at the Rhine Works of Mr. P. Clausen at Oberwinter, Germany. He has named it the Voith-Wassertrecker (Water Tractor) in consideration of the fact that, just as with the highway tractor, it is in reality a continuous crawling unit on the water with an engine-propeller combine of exceptional maneuverability. As shown in Figure 1, the *Biene* (Bee) is equipped with a non-reversible diesel engine of 120-150 BHP connected to the propulsion unit through a flexible coupling. The Voith-Schneider propeller used has a blade circle diameter of 4 ft. 7 inches and blade length of 2 ft. 1½ inches.

The wheelhouse and engine room cover are removable in one piece for overhaul work. The control stand in the wheelhouse consists of a steering wheel and a control lever for adjusting the propeller pitch in variable degrees from "full speed ahead" through "stop" to "full speed astern," the speed and direction of the diesel engine remaining unchanged. The operation of the engine is supervised at the control stand by the following instruments:

1. Speedometer.
2. Tele-thermometer (exhaust temperatures).
3. Lubricating oil pressure gauge.

In recent trials on the Weser River the author operated the *Biene* with no prior instructions and proved it to be highly maneuverable and capable of operating in close waters. An outstanding feature is that with this tug alongside a vessel being maneuvered it can be moved to port or starboard, as well as forward and astern, without shifting lines or tug position. A change in propeller thrust accomplishes any maneuver desired with excellent effectiveness.

As an example of her towing capabilities a hawser 15-feet in length was made fast between the stern of the MS *Drommel* (a 150-hp tug) and the MS *Biene* (115-hp). In three tests each tug pulled against the other and each time the MS *Biene* was able to take control of the MS *Drommel*.

Tests were also made concerning the extent of damage which would be incurred should the vessel go aground. At a speed of 8 kilometers per hour the MS *Biene* hit a sandy beach to such an extent that all personnel on board lost their balance. This test was repeated five times and then the tug was lifted with a crane to observe the results. There was no damage or deformities on either the propellers or propeller guards. This guard and after supporting fin are strong enough to support the vessel when drydocked.

From trial runs the following mean values were established:

Towline standing pull. 1.5 tons/100 hp

Stopping distance at
1.5 knots .....16 ft. (approx).

Time required to fully complete
a turn in its own circle..14 seconds

Fuel consumption.....0.4 lbs/hp/hr

It was found that with reduced hull dimensions, the use of constant speed engines, and the need for only one man to control the vessel from the wheelhouse, a one-man crew is sufficient. And by incorporating the maximum in maneuverability and the minimum in hull dimensions the field of operation of the vessel can be extended to shallower and more restricted waters.

FIGURE 1

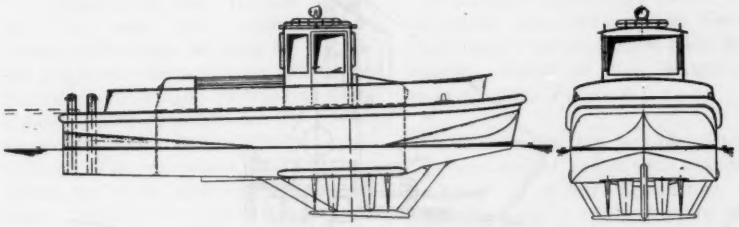
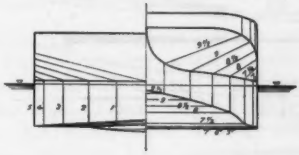
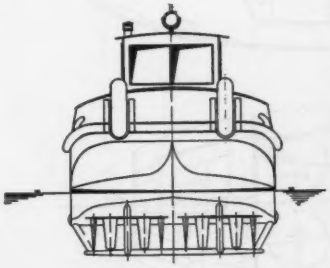


Abb. 4: „Biene", Längs- und Querschnitt



Length between perpendiculars- 10m 32'10"
Breadth, moulded 3m 9'10"
Draft to base of guard 1.4m 4' 7"
Displacement 12 tons
Effective horsepower 150 hp
Propulsion unit: 1 Voith-Schneider propeller Gr.14E3/65



Length between perpendiculars- 13.40m-44'
Breadth, moulded 4.25m-13'11"
Draft to base of guard- 1.60m- 5' 3"
Displacement 25 tons
Effective horsepower 2 X 150 hp
Propulsion unit: 2 Voith-Schneider propellers Gr14ET/ 55

FIGURE 2

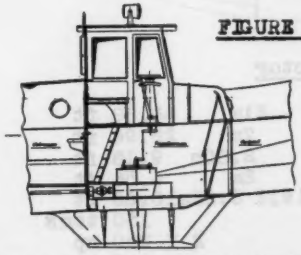


Abb. 6: „Hornisse", Längsschnitt des Vorschiffes und Querschnitt

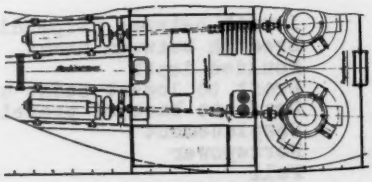
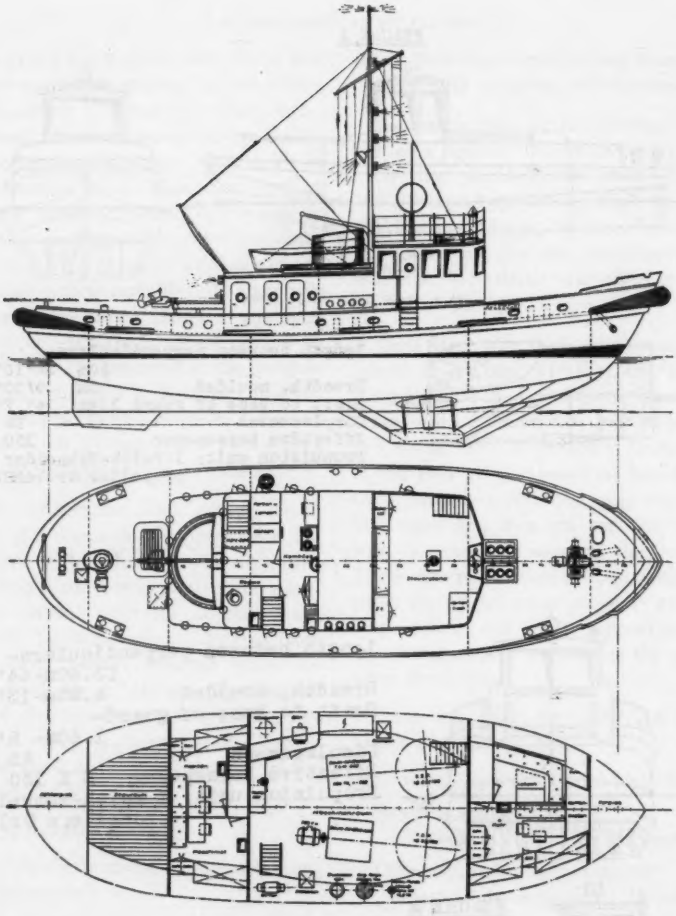


Abb. 7: „Hornisse", Deckplan



Sea-Going Tractor

Length between perpendiculars	21m	68.88 ft
Breadth between beams	7m	22.96 ft
Moulded depth	2.80m	9.18 ft
Draft to lowest point of keel	2m	6.56 ft
Draft to base of propeller shield	3.25m	10.66 ft
Displacement		150 tons
Horsepower		2 X 250 hp
Pull		6 tons
Speed		12 mph

FIGURE 4

FURTHER DEVELOPMENTS

A larger craft, the *Hornisse* (Hornet), has now been constructed to determine the value of using two cycloidal propulsion units side by side. (See Figure 2). Estimates of building costs indicate a 30% reduction compared with the conventional tug of similar capabilities. The propellers and engines (two) are of the same type used in the *Biene*. In order to extend the range of operations accommodations for a crew of two have been included.

An additional feature of this vessel are the two rubber truck wheels installed in the bow for use when the tug is pushing. These wheels rotate on their horizontal axis thereby rolling against the craft being pushed and minimizing wear and damage.

In further experiences gained from the *Biene* and *Hornisse* the German Waterways Administration have had a seagoing vessel of this design constructed. (See Figure 4.)

In this design the box-like lines of the *Biene* and *Hornisse* were abandoned in order to ensure satisfactory seaworthiness and a required speed of 12 mph. The breadth of 7m is based on two type 18ES/100 Voith-Schneider propellers.

Comparing costs with that of a similar tug of conventional design building charges were 57% less. Operations on an annual basis (for fuel, repairs, wages, etc.) were calculated to be 36% less.

BOOK REVIEW

DYNAMICAL OCEANOGRAPHY

By J. Proudman

C.B.E., M.A., D.Sc., F.R.S.

Professor of Oceanography, in the University of Liverpool

Published in London by Methuen and Co., Ltd.

in New York by John Wiley and Sons, Inc.

401 pages with 107 diagrams

First published in 1953

This book is intended for the use of students and of those engaged in practical oceanography.

The book contains a mathematical treatment which does not extend beyond elementary differentiation and integration in the main part. Partial differential equations are used freely in the second half.

The Chapter titles are: I. Gravity and the Rotation of the Earth; II. Continuity and Acceleration; III. Pressure; IV. Gradient-Currents; V. Stationary Accelerated Currents; VI. Turbulence; VII. Mixing of Sea-Water; VIII. Internal Friction in Parallel Currents; IX. Internal Friction and Geostrophic Effects; X. Thermodynamics of the Ocean; XI. Seiches in Lakes and Tides in Gulfs and Channels; XII. Long Progressive Waves; XIII. Response to Tide-Generating Forces and to Varying Atmospheric Pressure; XIV. Frictional Effects on Tides and Seiches; XV. Internal Seiches, Tides and Waves; XVI. Waves of Short Period.

Each chapter begins with an "Introduction" and ends with a "History." The latter credits previous workers in the field and references and an extensive bibliography.

BOOK REVIEW

SIMPLIFIED DRAFTING PRACTICE

By William L. Healy and Arthur H. Rau

Published by John Wiley & Sons, Inc., New York and
Chapman & Hall, Ltd., London

1953, 156 Pages, $5.00

Reviewed by George F. Fonger

This volume presents a modern approach to industrial drafting. The text, liberally augmented with illustrations, describes how drafting procedures can be simplified and yet convey precise engineering instructions about the shape, size, and material requirements of a part or an assembly to facilitate its manufacture. Many useful techniques in a large variety of applications are described in chapters under the headings of Simplification, Eliminating Unnecessary Work, Freehand Drawing, Use of Symbols, Mechanical Aids, Abbreviations, Arrowless Dimensioning, Legible Lettering and Tolerances. Additional chapters on the Use of Instructions, Drawing Forms and Related Routine, and Reproduction Processes are also included. The appendix consists entirely of examples comparing drawings prepared in the conventional manner with those prepared in the simplified manner.

This publication is of special value to those associated with engineering and drafting organizations. It should stimulate interest in the substantial savings that can be realized through the adaptation of simplified practices.

BOOK REVIEW

SHIP AND BOAT BUILDER

ANNUAL REVIEW 1953

COMPILED BY THE EDITORIAL STAFF OF
"SHIP AND BOAT BUILDER"

PUBLISHED IN LONDON BY JOHN TRUNDELL, LIMITED

PRICE IN LONDON: 30 SHILLINGS

With a foreword by A. E. K. Rodgman, Immediate Past President,
Ship and Boat Builders National Federation

The review contains 12 articles on such subjects as "Ordering a Coastal Tanker," "Light Alloy Craft on Tropical Service," "Radio Navigational Aids in Small Ships," "Plastics, Decorative and Purposeful Applications."

The main body of the book is devoted to a directory of Boat Builders in Great Britain and Overseas, a section on specifications of Brovine engines, one on "Materials, Fittings and Equipment" and additional directories of Consultants (Great Britain); Associations (Trade, Learned Societies and Miscellaneous); British owners of small craft; Dock and Harbor Authorities of Great Britain and Ireland; Commercial Diplomatic Officers and Trade Commissioners; and British Chambers of Commerce

DIED

Since the publication of the May, 1953, Journal, the Society has learned of the following deaths among its members:

WELLBROCK, J. HOWARD, Naval Member

BANNER, OTTO, Civil Member

MEMBERSHIP CHANGES

It is with much pleasure that the Society announces that the following have joined the Society since the publication of the May, 1953, JOURNAL.

NAVAL

Augustine, Pasquale Robert, Ensign, USNR,
Engineer, Westinghouse Electric Corp.
Mail: 4866 E. Broadway, Tucson, Arizona

Barr, Eric L., Jr., Captain, USN, Ret.,
Standards Manager and Security Director, Electric Boat Div.,
General Dynamics Corp.,
Mail: Oswegathie, Waterford, Conn.

Burnett, Carl Frederick, Ensign, USNR,
Design Engineer, Sparkman-Stephens, Inc.
Mail: 114-23 173d St., St. Albans, L. I., N. Y.

Callahan, John Joseph, Lieutenant, USN,
11 Birch Hill Road, Newton 60, Mass.

Davis, Alan Chenery, Captain, USNR,
President, Viking Instrument Co.,
Mail: Hadlyme, Conn.

de Laski, Arthur B., Lieutenant (j.g.), USNR,
Sales Manager, Welin Davit and Boat Division,
Mail: 500 Market St., Perth Amboy, N. J.

Dingle, Victor Stanley, Lieutenant, USN,
Performance Engineer, Esso Shipping Co.
115 Broadway, New York 6, N. Y.

Dyer, John Calvin, Lieutenant, USN,
27 Bromfield St., Watertown, Mass.

Frederick, Halsey A., Jr., Lieutenant, USNR,
Leslie Company,
Mail: 166 Laurel Hill Road, Mountain Lakes, N. J.

Frederick, J. Lawrence, Commander, USNR,
Contracting Group, R.C.A. Victor,
Mail: 415 First Ave., Haddon Heights, N. J.

Lemler, Philip, Captain, USN, Ret.,
General Manager, (Shipbuilding) Todd Shipyards Corp.,
Mail: Box 2586, Houston 1, Texas.

McMullen, John Joseph, Commander, USN,
Code 430, Bureau of Ships, Navy Dept., Washington, D. C.

Mare, Acton Lawrence, Captain, USN, Ret.,
Assistant Manager, Ship Repair Sales, Bethlehem Steel Co.
Shipbuilding Div., 25 Broadway, New York 4, N. Y.

Morse, Robert Hosmer, III, Lieutenant, USNR,
General Manager Beloit Works, Fairbanks, Morse & Co., Beloit, Wis.

Raymond, John Walker, Lieutenant, USNR,
Engineer, Gas Turbine Engineering Dept., Westinghouse Electric Corp.,
Mail: 2367 Chipmunk Lane, Holmes, Pa.

Reardon, Robert Wilson, Lieutenant (j.g.), USNR,
USS *Adria* (AP 30), % Fleet P.O., New York, N. Y.

Singer, Isaac Merritt, Jr., Ensign, USNR,
1335 Florida Ave., Corpus Christi, Texas.

Spriggs, William Brown, Lieutenant, USNR,
Mech. Engr. Public Housing Administration,
Mail: 612 Clifton Road, N. E., Atlanta, Ga.

Stock, Edward J., Lieutenant, USN,
Route 4, Box 495 B, Stono Park, Charleston, S. C.

Wolff, Marvin M., Ensign, USNR,
Design Engineer, Sparkman-Stephens, Inc.
Mail: 1563 West 10th St., Brooklyn 4, N. Y.

Zettel, Ralph Anton, Lieutenant, USN,
USS *Cimarron* (AU 22) % Fleet P.O., San Francisco, Calif.

CIVIL

Brackett, John Frederick, Chief, Ventilation, Heating and Air Conditioning Sec.,
Maritime Administration, Dept. of Commerce,
Mail: 4428 Butterfield Place, N. W., Washington 16, D. C.

Chandler, John W., Marine Representative, York Corp.,
Room 1014 DuPont Circle Bldg., Washington, D. C.

Curtis, Sidney Roby, Vice President, Govt. Contracts, Stromberg-Carlson Co.,
Mail: 100 Carlson Road, Rochester 3, N. Y.

Greene, Elliott L., Electrical Engineer, Supervisor, Shipbuilding, USN & NIOrd,
Mail: 880 47th St., Brooklyn 20, N. Y.

Moore, MacCormick G., President,
Empire Steel Castings, Inc., Reading, Pa.

Muirheid, John Guild, Sr., Mech. Engr., Bureau of Ships, Navy Dept.,
Mail: 3413 Beacon Lane, Falls Church, Va.

Ness, Harold J., President, The Lithium Co.,
110 Sylvan Ave., Newark 4, N. J.

Olsen, John Karl, Engineer, Ingersoll-Rand Co.,
Mail: 3110 Dickinson St., Camp Hill, Pa.

Paganelli, Thomas I., Manager, Marine & Ordnance Radar Engineering, Electronics Division, General Electric Co., Syracuse, N. Y.

Parker, Herbert E., Supervising Engineer, Bethlehem Steel Co., Shipbuilding Division, Mail: 74 Sealund Road, Quincy 71, Mass.

Signorelli, Alfred A., President Design Service Co., 50 Broad St., New York 4, N. Y.

ASSOCIATE

Alexander, Lee K, Sales Manager, Govt. Products Marketing, Electronics Division, General Electric Co., Syracuse, N. Y.

Barrett, Bracell, Owner-Manager, Barrett Machine Works, Mail: 1109 Hub St., Houston 23, Texas.

Barth, H. Wade, Chief Engineer, Cleveland Diesel Engine Div., GMC, 2160 West 106th St., Cleveland 11, Ohio.

Dole, M. E., Factory Supt., Beatrice Steel Tank Mfg. Co., Mail: 406 Beluiclen St., Beatrice, Neb.

Jordan, John Pendleton, Jr., Code 541, Bureau of Ships, Navy Dept., Mail: 4201 25th St., No., Arlington 7, Va.

Konig, Herman F., General Manager, Light Military Equipment, Electronics Div., General Electric Co., Utica, N. Y.

Poolman, Justus Cornelis Humphrey, Lt. Comdr. (E) R. Neth. Navy, % Mrs. A. Gyravan Bennekom, Huron Church House, 476 Richmond St., London, Ontario, Canada.

Sheets, George, Washington Representative, Stromberg-Carlson Co., 810 18th St., N. W., Washington, D. C.

Sorenson, Hans S., U. S. Dept. of the Army, Yokohama Engineer Depot, Supt. of Itomatso Mfg. Co., Mail: YED, MAINT. Div. Det. "A" 8055 AU, APO 503 % Postmaster, San Francisco, Calif.

REJOINED

Bennett, Roy G., Associate.

Dunning, Allan L., Naval.

Rados, John C., Civil.

TRANSFERRED ASSOCIATE TO CIVIL

Vanina, R. A.

ASSOCIATION NOTES

ORIGINAL ARTICLES

The editor of the JOURNAL is most anxious to obtain manuscripts of original articles on subjects of interest to naval engineers. Any manuscript accepted for publication becomes the property of the Society which copyrights it upon publication. Authors are paid from $40.00 to $150.00 depending upon length, interest and professional value.

The rules for manuscripts are as simple as we can make them.

1. They must be legible (typewritten, double-spaced preferred) since no proof is submitted to authors for correction prior to printing.

2. Single copy only is required.

3. Mathematical formulae used must be set up, preferably by hand printing, so that there can be no question as to symbols, subscripts and exponents.

4. Any drawing submitted must be black on white. A cloth or paper tracing is acceptable but not required.

5. Photographs may be negatives, but glossy prints are acceptable.

6. Include on a separate page a short biographical sketch(es) of the author(s). 50 to 100 words for each author is desired.

Manuscripts should be mailed addressed to:

Secretary-Treasurer
American Society of Naval Engineers
605 F St., N. W.
Washington 4, D. C.

Manuscripts accepted will not be returned unless specifically requested by the author. If returned, they will be in the condition which has resulted from the work of the printer and the engraver. Immediately following publication, the author is furnished 10 reprint copies of his article free of charge. Additional copies may be purchased from the Society if the request is received 30 days prior to the publication date which is the 25th of the issue month. Estimate of cost of additional reprints, which will vary with the nature of the article and the number of copies ordered, will be furnished on request as soon as possible after the article is set up.

Manuscripts not accepted will be returned, postpaid, by the Society.

Manuscripts which are accepted will be published in the earliest JOURNAL which has not yet been closed (60 days before publication) and for which insufficient material is already on hand.

SUBJECT MATTER AND AUTHORS

To assist the editor in programming future issues, the help of all members is solicited. To make it easy, the last page in this issue is readily detachable as you will find. This page has blanks for two entries.

(a) What subject would you, as a member, like to see covered by an article in the JOURNAL.

and

(b) Who do you consider best qualified to prepare such an article authoritatively, and what is his address (if you know).

Any of these forms which are filled in and mailed to the Society will be received with thanks and the editor will follow up to get the suggested articles prepared.

PHOTOGRAPHS

Photographs of current or historical interest to readers of the JOURNAL are desired. Any which are accepted by the Society will be purchased by the Society at a standard price of $5.00 each. Such purchase *will not* include any copyright by the Society, but the contributor must hold the Society free from any charge of violation of any previous copyright.

NOTICE OF DEATHS

The Society has no satisfactory machinery for obtaining notice of deaths of members. It is particularly desired that we receive such notice upon the death of any past officer, past member of the Council or member of more than twenty years' standing with photographs and short obituaries. It will be appreciated greatly if any member who learns of the death of a member will advise the Secretary-Treasurer.

SOCIETY LAPEL BUTTONS

Shown below is an illustration of the lapel button of the Society. It is believed that it will be conceded that this is a very fine dignified insignia. It is one-half inch in diameter.

The oak leaves and lettering are red on a gold background.

It is available to all members at fifty cents (50c) each.

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a) Credit is given to the JOURNAL with reference to the issue.

b) Credit is given to the author.

c) If the author is a military officer or a civilian employe of the Department of Defense, the following note shall be carried:

> "The views expressed herein are the personal ones of the author and are not necessarily the official views of the Department of Defense or of a Military Department."

DEFENDERS OF FREEDOM

Our United States Navy submarines with their superb crews will help protect our shores and our shipping from possible enemy undersea craft. Supreme dependability and instant response are required of engines and crews. The United States Navy has installed General Motors engines with Diesel-Electric Drive in submarines of this new "K" class.

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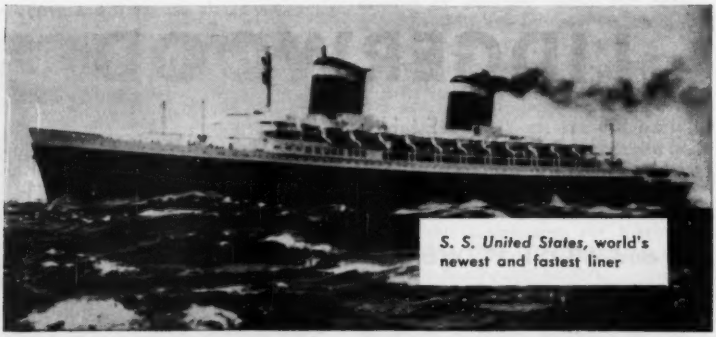

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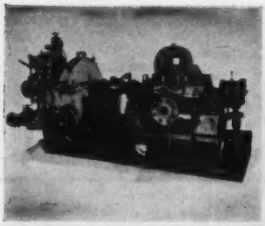
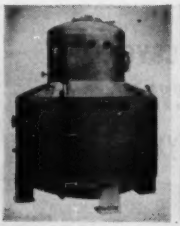
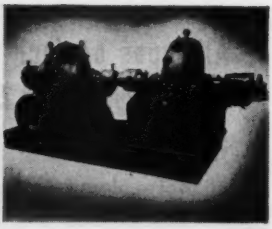

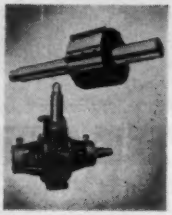
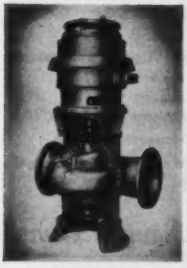
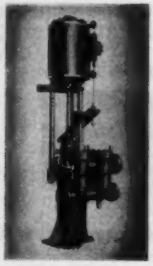
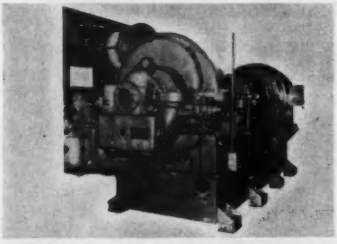
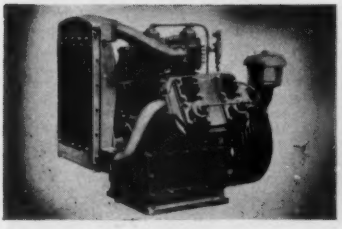

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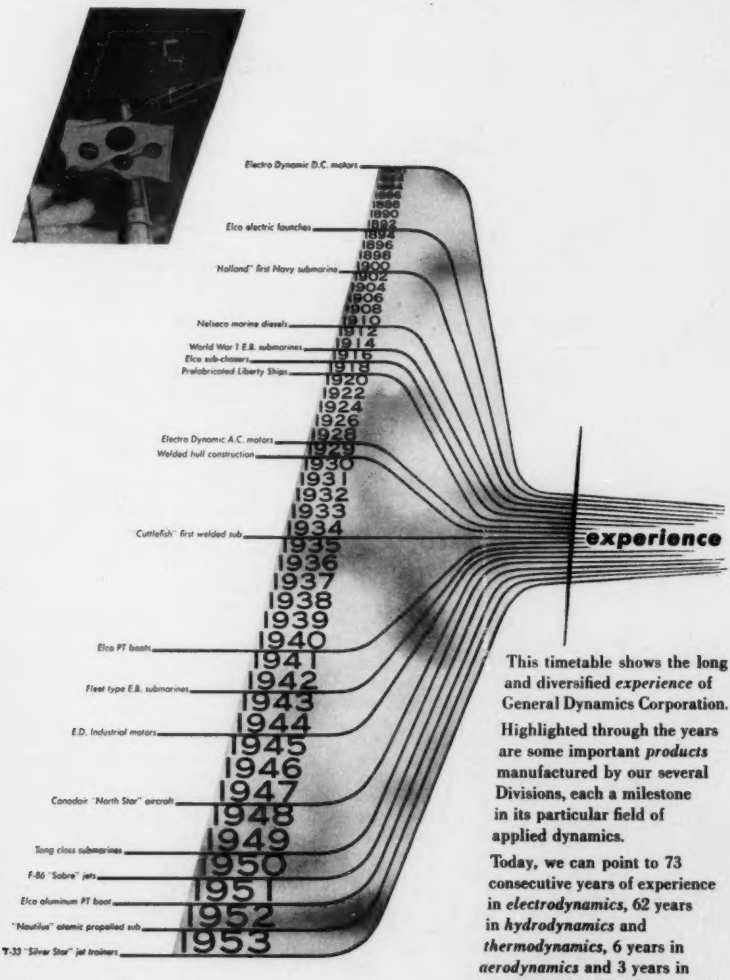

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